A S Q C

CONFERENCE PAPERS

FIRST ANNUAL CONVENTION
AMERICAN SOCIETY FOR QUALITY CONTROL

and

M Q C C

SECOND MIDWEST QUALITY CONTROL CONFERENCE

HOTEL SHERMAN

CHICAGO, ILLINOIS

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CONFERENCE PAPERS

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FOREWORD

Publication of Conference Papers represents a new venture on the part of the general Conference Planning Committee. It was proposed to bring together in one volume as many of the Conference papers as could be released for publication in this book, and to make this material available to the quality control public at cost. That these objectives have been achieved is due (1) to the excellent planning of the Program Committee which secured the program speakers and encouraged their participation in this publication project, (2) to the exceptionally fine cooperation of the program speakers in submitting carefully prepared manuscripts of their papers well in advance of the conference date, and (3) to the skilful handling of this material by the staff of the John S. Swift Company at a time when it was especially difficult to get a book of this sort published in any form. Without the benefit of these three factors, no amount of effort on the part of the Proceedings Committee could have brought this book into being at any price.

Responsibility for the context of each paper resides with its author, the Proceedings Committee undertaking only to see that technical and typographical details in the book are in harmony with the manuscript submitted. It is, perhaps, too much to expect that the material published is entirely free from mechanical errors, but it is hoped that any such irregularities will not be misleading or confusing.

Acknowledgement is due the program speakers (clinics 3-9-13-16-21-23-27-33-35) whose papers are not included in this book. Circumstances beyond the control of the respective speakers made these omissions necessary. Their participation in the Conference was nevertheless most welcome, and served greatly to strengthen the program despite the fact that they were not able to contribute their papers to this book.

The Proceedings Committee, as the agent of the general Conference Planning Committee, takes this means of expressing its appreciation to all those whose cooperation has made possible this publication, and its hope that the reader will derive benefits commensurate with the efforts and abilities of the authors.

Proceeding Committee
Midwest Quility Control Conferences
Chicago, Illinois, 1 9 4 7

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WHAT TOP MANAGEMENT EXPECTS FROM QUALITY CONTROL

C. R. Sheaffer, President
W. A. Sheaffer Pen Company

We are all aware in this immediate, post-war period, competition together with a buyer's market is forcing the manufacturer to produce a higher quality product than ever before, with corresponding decreased costs; and all this in the face of rising material and labor costs. Anyone can turn out junk, and many firms are doing this at the present time, selling their products very freely in the market. The future of these companies is not too bright. In the final analysis, the consuming public will decide which quality product they want, and we want them to decide on ours. The advent of new precision, engineered, quality products with their extremely close tolerances, compared to pre-war standards, demands that we all become increasingly quality minded. It is imperative we must now concern ourselves as never before with increasing quality, because we know that as competition becomes more keen, the ability to win and hold a market will constantly bring into focus the importance of producing a quality product which will justify acceptance by the consumer. The consuming public is becoming more critical both in price and quality, and it has a perfect right to become critical. Thus, we must make use of this newest management tool, QUALITY CONTROL, to [illegible]e maintenance of top quality, at lowest cost.

We make a quality product. We believe that we have been especially imbued with the quality tradition, because our founder, my father, who developed the first successful lever filling mechanism for a fountain pen, was originally a retail jeweler for many years, selling only the highest quality watches, silverware, etc. We believe he made an indelible impression upon our organization regarding the policy "Quality First", and he has left us a heritage to follow. We have always felt, down through the years, that this philosophy of giving continuously greater quality has been quite definitely a matter of habit. When times became tough a number of years back, while others might have cut prices and also quality in order to maintain a market, we improved quality to maintain our position. Top management cannot relax for one instant in its attitude toward maintenance of quality standards. This attitude must be reflected down through the entire organization to each employee. This attitude must be carried through systematic and scientific procedures regarding quality standards. It is our belief this newest management tool, Statistical Quality Control, can and is aiding materially not only in the maintenance of quality, but the improvement of quality with corresponding decrease in costs.

Thus, it was only natural that our manufacturing executives took advantage of the opportunity offered by the State Universities to obtain scientific, detailed, intensive instruction on Industrial Quality Control during the latter part of the war period and immediately following. I say that it was only natural for two particular reasons, namely,

1. Because of our constant search for ways and means to maintain and improve the quality of our products.

2. During the extremely trying war period our company produced vital, precision, timing devices for all the military services, and these were accepted on a quality control sampling basis by our Resident Ordnance Inspectors, and Navy Inspectors.

You have asked me the question "What does top management expect from Quality Control?" Without going into the technical aspects, or delving into the engineering techniques involved, and without knowing the laws of probabilities, I believe we can expect the following:

1. A change in quality consciousness.
   By this we mean that through the use of quality control chart techniques and sampling directly at the machines in the shop, we are changing the attitude of employees and supervision from the former philosophy of "that's good enough," to, "now it must be better." We feel that by the use of quality control charts suspended on the machine directly in front of the operator, we are furnishing him a new positive guide to go by, showing him the desired level of performance so that he can reduce rejects to a minimum and make readjustments before he has reached the reject area or scrap area. Our employees use their charts as an advertisement of their good work. They take pride in showing off their quality.

2. A change from the negative type of inspection to the positive type of inspection.
   Formerly, the old idea was for inspection to find as many things wrong with an article as possible, to throw out as much as they could. Now, our inspectors act as a councilor, showing production operators and supervision where they are deviating from the desired level of performance, how far they are deviating, and when to adjust the process, turn off, sharpen the tool, etc. to bring the process back into perfect adjustment for good control of quality. Our inspectors now use this positive type of inspection, of showing when quality is deviating from the desired level, before scrap has been made, instead of merely sorting out the bad from the good after the parts are made. In this connection we like to think of the negative type of inspection as a culling out or sorting proposition, merely picking the bad parts out from the good, but too late to correct them. This is very similar to locking the barn door after the horse has been stolen. It's too late to take corrective measures when parts are finished.

3. Starting the new employee out in the right quality frame of mind.
   We are now employing in several departments a policy of the departmental foreman, when initially meeting the new employee, taking him or her into his office and explaining

the analogy of the concrete highway proposition with its attendant soft shoulder and subsequent ditch as comparable to our quality control charts on the machines. I believe that many of you are familiar with this comparison, namely, how the concrete highway is the safest place to travel, that it compares directly with the area on our quality control charts between the upper control limit and the lower control limit. As long as we keep our work or plottings between those limits we are producing as good work as possible. The area between the edge of the concrete highway and the ditch, which we call the soft shoulder, is comparable to the space between the control limit and the blueprint specification. While one does not produce scrap or rejects in this area, nor does one wreck his car while riding on a soft shoulder, he is in a dangerous position and any moment can go into the ditch or allow his dots or work to jump over the blueprint specification into the scrap area. Thus, it tells the operator to get back between the control limits, stay on the concrete highway as much as possible. We use this story very forcefully to our new employees, together with showing them a large, colored picture of the concrete highway and a corresponding picture of our quality control chart, so that when they go out to their first job the principle of not only controlling quality but maintaining and improving it is utmost in their mind. We feel they start out on the right foot.

4. We expect Quality Control to furnish facts and information to our supervisory staff, department managers, etc., regarding the exact working limits possible on our various production machines.

That is, we want to know, if a machine will not hold a required tolerance, how much scrap can be predicted under present conditions, and what measures can be taken to eliminate the assignable causes that create rejects. We expect Quality Control to make sufficient samplings at these machines to furnish our engineering department with data that will allow them to establish working tolerances in accordance with our demands, etc. If the checks made by Quality Control indicate the machines will not give us the required quality, our management and engineering staff can make the necessary changes either in the machine or process so that we will obtain the desired quality.

5. We expect Quality Control to aid the Purchasing Department in establishing better vendee-vendor relationships regarding the many parts, materials, supplies we purchase outside.

We have found our suppliers welcome the opportunity of sampling material at source to determine the per cent defective before shipping, so that when we inspect by quality control sampling upon arrival, the vendor will know what per cent defective parts we will find in the lot. In other words, we can place on our purchase order the acceptable quality level we must have so that the vendor can manufacture the parts to meet our A.Q.L. and will know when we sample upon arrival, they will meet this A.Q.L.

6. We expect Quality Control to adequately control our manufacturing processes regarding dimensions, tolerances, etc., by quality control charts directly out in the factory on machine or assembly operations, so that our inspection (which is overhead) is held to a minimum, consistent with our desired out going quality products, so that ultimately we may be able to merely use the quality control sampling system to replace the expensive, costly 100% inspection, which is nothing more or less than a sorting operation.

100% inspection never improves quality. In this connection we expect Quality Control, with Inspection, to institute sampling procedures at strategic inspection stations for the maintenance of quality standards as the lots pass through the shop. Likewise, by quality control sampling we expect to obtain assurance that the desired quality is in the remainder of the lot without having to resort to 100% inspection. I might cite a specific example in one or our manufacturing departments where we had ten assembly operators assembling several items, with two 100% inspectors checking all the work. Later on, in the same department, 200% further inspection was given these same items, and still later, when these finished parts passed to another department we had continual complaints regarding poor quality. Thus, with 300% inspection we were still not obtaining the desired quality level. We have since removed the 300% inspection, thus allowing us to use this inspection talent in other needed places. These assemblies have been placed on a lot-by-lot quality control sampling basis, making the assembly operators (who are, incidentally on an incentive basis), responsible for their own quality. We have a quality acceptance chart directly in front of the ten operators, showing their daily quality level, and where we ask for a 2% acceptable quality level, the process is actually averaging at this time .3%. All of the operators are cooperating most willingly, and make as much money as before. The department manager reports a direct saving of approximately $40.00 each day. I could go on and cite other similar instances with corresponding savings, but the beauty of the above example is that now the department that receives this assembled product no longer registers any complaint regarding faulty parts. The responsibility for good work now rests with the operators.

7. We expect Quality Control to make adequate daily samplings in our Repair Department, of all production, and daily plotting the per cent defective so that all personnel as well as management will know the out going quality level.

We also expect Quality Control to be able to tell us those employees who are not repairing our merchandise properly, through quality control sampling, so that we might give these employees further training in quality workmanship. We also expect Quality Control to analyze our customer complaints in this department so that we will know by factual evidence where necessary corrective measures must be taken.

8. We expect Quality Control to keep our various supervisors, department managers, and manufacturing executives informed of our relative quality position constantly, with sufficient management charts.

   We like to call them dollars and cents charts. We expect Quality Control not to furnish our busy manufacturing executives with weighty statistical data, thousands of figures, etc., but boiled down, precise, charts on a day by day basis, week by week, as well as monthly averages, showing the quality level in relation to an upper control limit, so that our foreman, supervisors, department managers, can take the necessary corrective action to eliminate those assignable causes that cause these charts to go out of control.

9. We expect Quality Control to keep the supervision of our manufacturing departments constantly informed by quality control charts regarding operators who are not maintaining desired quality levels on the control charts.

   That is, these charts can tell us in very short order whether an operator has had insufficient training for the job, whether he lacks the coordination to perform the job, whether he is in poor health, etc., and cannot adequately handle the processing we demand. In many cases supervision can give further training to keep operators within the upper and lower control limits, or transfer to more suitable jobs, those workers who cannot coordinate their efforts to produce the desired levels we require.

In passing, there are several axioms I'd like to leave with you:

1. In placing a quality control chart on an operator's machine or process, tell him everything, but explain it in shop language.

2. Give credit when credit is due for good work. If a fine quality control chart is completed and shows good control, let the employee know it by writing him a note, a pat on the back, or post the chart on the bulletin board.

3. Ask for the operator's advice as to the best location for a quality control chart, when placing it on his job. Instead of arbitrarily placing it where you want it, ask the operator "Where would you like to have this control chart hung so that it will best show off your good workmanship to your co-workers and supervisors?" In other words, let him tell you where he would like it. It makes him feel that he is part of the organization, and that you have a personal interest in him. It pays off.

4. Where possible, create a friendly spirit of competition with your quality control charts. For example, we had a lathe bench with five lathes on each side, all performing the same operation on the same type of part. We placed two charts out on one side of the bench and soon operators on the opposite

side of the bench were asking for quality control charts so that they might also show off their workmanship. Soon there were placed ten quality control charts on these ten machines in such a manner that operators on the opposite sides of the bench could see the other's control charts. It certainly created a spirit of competition, and soon the charts came into good control and remained there.

A new and healthy relationship exists between our Quality Control Department and our Methods Engineering Department. That is, quite often the methods engineer desires to improve a particular operation or job. He finds that it is out of control, and therefore, calls upon the quality control engineer to study the job and apply quality control to produce the desired quality. When control of quality has been attained the methods engineer can proceed. Likewise, the quality control engineer will find he cannot adequately install quality control in a process or a department until the methods engineer has made a revision or improved methods that will insure management's desired quality.

There is one particularly pleasing incident (among many that I could relate to you) regarding one of our employees on a grinding operation. He was asked to consider taking another job of a different nature because he was needed, but stated he would rather stay on this grinding operation as he was now averaging 5¢ or more per hour in his wages than formerly. When the foreman inquired why he was making more per hour now since no changes had been made in the process or rate, he plainly stated "You have quality control upon the preceeding operations that control the diameter and length of the two parts I receive as an assembly. These now come to me so uniform that I have to dress my wheel less often, make less set-ups for variation in length and diameter than formerly; thus, I can grind for longer periods on the same set-up, produoing good work." Here's a good example showing how everyone benefited, the employee as well as the company.

In closing let me state that we have only scratched the surface with our quality control program. We make no outlandish statements as to huge savings in dollars and cents, and we never expect to make such statements. We're after greater quality at less cost, with corresponding benefits to all. We have a long way to go, and at the present time I believe we only have 500-600 charts in the shop, while we have several thousand various types of machine and assembling operations.

We at Sheaffer Pen work as a team to achieve better quality at less cost. Everyone must be quality conscious and possess the correct quality attitude. All of management's quality objectives cannot be accomplished by merely instituting a quality control program. Quality control is not an isolated function. There must be close cooperation between Engineering, Production, Inspection, the man or woman on the job, and Quality Control. The entire organization must strive to do its best in the control of quality if our writing instruments are to receive the most favorable reaction from the consuming public.

A MANAGEMENT VIEWPOINT OF QUALITY CONTROL

George F. Smith, President
Johnson & Johnson

The factor of quality has always been important to responsible businessmen. In fact, the success of any business enterprise, in the final analysis, depends upon quality of service, quality of product, or both.

The war brought in its wake many problems, incidental to the military scene, but nonetheless inconvenient or unpleasant to the public at large. The quality of service was too often absent or neglected. In the shops of the land, in restaurants, hotels, and other service institutions, the customer was a sorry victim of a "seller's" market. Discourtesy, slovenliness, sheer filthiness in some cases were just some of the examples of a degradation of quality that must be corrected and will be corrected in the buyer's market which is on our threshold--in fact with us today in some instances.

A great deal might be said about that phase of quality, but we are here primarily concerned with product quality and pertinent control techniques.

So far as civilian goods are concerned, the war period and that immediately following had an interesting effect. Many tried and true products disappeared from the market or were in short supply. Familiar brand names had in some instances vanished from the dealers' shelves. Many well known products were available in only limited quantities.

It is immaterial whether this was because the manufacturers' facilities were largely devoted to war production--or that quality raw materials were short--or that the manufacturer preferred to avoid prositituting his good trademark by placing it on a package containing a product of low standard.

The fact was, and to some extent still is, that the consumer was frequently obliged to buy substitute products, many of inferior quality, or go without. Every one in this room, I venture to say, has had the experience of buying, with misgiving, an unknown brand of product. The misgivings you had at the time of purchase were, as you know, too often confirmed when you put the product to use. This condition was so widespread that the public, with an almost audible sigh of relief, gobbled up supplies of familiar branded merchandise as fast as they hit the market. The honeymoon is over so far as poor quality substitutes are concerned.

Now quite obviously there is a moral here, and an opportunity. The public has learned the hard way that established brands of products are based on quality. The public has had a liberal education in the fact that familiar trademarks have more behind them than advertising expenditures. The people of America are turning with high expectations to old product friends. There is a rich reward if the quality is as

superior as they hope—there is business disaster for the manufacturer who fails to satisfy that expectation.

There is a significant warning in a speech recently made by Wm. H. Howard, Executive Vice President of R. H. Macy & Co. Referring to quality he said:

> "Retailers are growing increasingly dissatisfied with the quality of much of the merchandise they are receiving. The war has been over for a year and still a lot of the stuff that is coming through is not good. They understand that it was inevitable that there should be a let down in quality standards during the war. They understand the problems that the manufacturer had with materials, supply, labor turn-over, and all the other factors that contributed to a poor product. But both retailer and manufacturer know that the turning point has come in this matter of quality and that the time is here when something more than lip service is needed. And don't blame the retailer if he seems to be particularly sensitive on this point about now - because he is on the receiving end of customers' complaints, and the complaint line on his charts is going up faster than the sales curve.
>
> Many types of manufacturing call for high standards, both as to the material used and the methods of fabrication, but not enough attention has been given to the setting up by some industries themselves of minimum standards. More and more regulations are being issued by the Federal Trade Commission and other regulatory bodies to insure the customer getting what she is paying for. It is time for more industries to initiate this corrective work themselves and not wait for outside pressure to bring it about. Better products made to higher standards, better inspected, and better packaged, are not only essential to the manufacturer but are a tremendous assistance to the retailer in his attack on the problem of high operating expense."

Practically every manufacturer establishes a high quality standard for his product. The specifications are carefully drawn, and the manufacturing procedures are painstakingly established. Too frequently the control of quality is lacking in its efficacy and especially so where the small shop with its meticulous craftsmen has been supplanted by mass production methods and semi-skilled workers. Incentive wage plans while reducing labor costs have placed a new burden upon quality control.

In the surgical dressings industry we have an unusual set of circumstances. Largely inspired years ago by the industry itself, the United States Pharmacopeia establishes quality minimums and prescribes the labeling requirements. The Pure Food and Drug Administration is set up to insure conformance to the USP regulations.

The responsible manufacturers in our field recognize a health responsibility. It is therefore natural that we and others have encouraged the tightening of USP regulations wherever necessary. The

high standards of quality that result, we know, are to our benefit as well as that of the doctor, the surgeon or the lay consumer.

Such standards obviously call for meticulous quality control. And yet, because the gross profit margins in our industry are relatively small--the cost of the control of quality must be in reasonable proportion.

For many years, and up to four or five years ago, quality control meant to us a very large staff of departmental inspectors. Supplementing this army of departmental inspectors was a large central control laboratory spot checking finished goods with a very critical eye. It wasn't until later that we realized that this inspection and testing after the event cost us a lot of money and, worst of all, often failed to focus our attention on the trouble spots responsible for rejects.

One day a sizable rejection came to my notice. Investigation developed that the deviation from standard occurred about 10% from the start of the manufacturing process. As our inspection system did not catch the deviation quickly enough, we had carried production of the item through the remaining 90% of the process--throwing good money after bad. There was a virtually complete loss of materials, labor and overhead.

It was a coincidence that shortly after this occurrence the Shewhart technique of control came to my attention. We had several meetings with persons skilled in the technique and then, with some misgiving, we tried this form of quality control in one of our departments. The installation was cautiously made, the personnel involved carefully selected, and fortunately the man chosen to direct the program had an engineering background and knew the statistical control methods and principles.

The results were very satisfying. The control stations had been carefully selected and, based on experimentation, tolerances were established. The very process of establishing the tolerances identified some opportunities for machine improvements or methods changes.

I say the results were very satisfying because not only were the factors of quality under better control, but we found additional advantages that were far reaching in their effect.

1. Where we had previously destroyed a sizeable percentage of production under the old inspection and testing methods we, somewhat overcautious at first, ultimately established statistical sampling denominators that sharply reduced such losses.

2. The carefully watched charts signalled any manufacturing trend out of the zone. Today we virtually never have a quality condition get out of hand before machine adjustments or other corrective measures can be taken.

3. Careful study of the charts enabled the manufacturing executive to improve his machinery--redesigning it where necessary--or to change his process to keep safely within the tolerance range.

4. While the tolerances in some instances were at first rather wide when viewed against our present day standards the statistical warning--the

running record of performance at each critical point in the manufacturing process, enabled us to narrow the tolerances to a remarkable degree.

5. One wholly unexpected result was the reduced tension of those in the production organization. Under the old inspection system several hours of several days might go by before the devastating word "rejected" came through. With our present system, quality control is right on the production line, and if anything goes wrong it is detected almost immediately. You can imagine what this means to the workers and the supervisors in the plant.

6. Most important of all, we were able to disband the army of inspectors and laboratory control technicians except, of course, the bacteriological sections. We now have instead a relatively small staff of technicians on the "firing" line controlling quality in a constructive way--finding and correcting causes for variations rather than accepting or rejecting with an indifference to cause. Instantaneous action is the keynote.

   Incidentally, when I refer to "disbanding" the old inspection staff, I assume it is unnecessary to say that our responsibility to the men and women involved was not ignored. Some became part of the new quality control organization, some were transferred to other posts for which they were suited--all received the decent and adequate consideration that is to be expected in any modern industrial organization.

The successful application of the statistical quality control technique or any new technique, for that matter, depends upon enthusiastic cooperation of the other parties involved. It was our experience that time spent to "sell" the manufacturing executives on the new type of quality control was invaluable. When they understood what we were trying to do and could see the benefits to themselves, we had no trouble installing a radically different technique. Incidentally, don't forget the workers--even though all of them may not readily understand your story. They like to feel a part of the show, and if you will encourage them to do so they will eagerly assist toward the attainment of your objectives instead of throwing hurdles in your path. If there is a union in your plant, see that the union officials are informed in advance. They will readily see the value of quality control and often help to overcome prejudices that might exist.

There is, of course, much more that can be said, but I have about taken my allotment of time. I want to seize this opportunity, however, to express our gratitude for the opportunity given our key people in quality control who were invited to participate several years ago in the intensive training program at Princeton University and at the State University of Iowa. Much of what we learned there has contributed toward the high standards of quality control that we have today in Johnson & Johnson. Further, I should like to voice the thanks of businessmen generally for the excellent work of the American Society for Quality Control in keeping management and our technical people abreast of new and useful developments in your field.

Supplying the consumer is, after all, a matter of teamwork. If we work together as we should, we can adequately discharge our primary responsibility to the American public which deserves and will insist upon quality merchandise, good service, and reasonable prices.

QUALITY CONTROL AT ALDENS

Robert M. Jackson, President
Aldens, Inc.

I want to keep this paper simple and straightforward. Aldens is interested in quality control because:

1. We must be sure quality has been built into the products we sell.
2. We must assure ourselves that all of our merchandise is of a uniform quality, and that it meets our rigid specifications.
3. The only way we can stay in business is to control the accuracy with which we fill and assemble customers' orders for shipment.

Later, I shall review each of these factors, attempting to show the part quality control plays in our distributing merchandise to over 3,000,000 customers.

The word "quality" to us is synonymous with "customers". One is dependent upon the other. Our future is dependent upon the quality that is built into our merchandise and upon the controls we exercise in serving our customers. Quality control in its broadest sense concerns the systematic control of variables - materials, men and machines. Through a scientific sampling technique, errors and irregularities are isolated and causes corrected, resulting in improved quality and service. High quality generally means higher costs, whereas relaxed quality may permit lower costs, but eventually a loss of customers. The orthodox inspection operation is likely to be non-productive, whereas the control of quality is productive, and is certainly worthy of every consideration. All control should start with planning - pre-planning - and not begin after difficulties develop. Quality cannot be inspected into merchandise. Therefore, our paramount interest is the control of quality, and we readily endorse the new modern and scientific systems that help us to segregate, report, follow-up, and correct all types of irregularities.

A logical step would be to give you a bit of Aldens background and review for you our situation. We have been interested in quality for 58 years and have accepted this guarantee. "We guarantee every article in our catalog to be the best quality obtainable anywhere at our price, and that it will give you the service you have a right to expect for the price you paid". We buy merchandise from 18,000 sources. Our catalogs illustrate 14,924 different items, with most items carried in a wide variety of colors and sizes. In 1946 we checked in 37,407,630 pieces of merchandise, and shipped to our customers 11,320,175 packages. We have an operating staff of approximately 5,000 employees. Every single individual item of merchandise is handled by close to 100 people in either our plant or at the manufacturers' before it ultimately reaches the customer. That human factor alone would justify our sincere interest in quality control.

The day of reckoning is at hand, and we know that the merchants who obtain and keep their customers are the merchants with a reputation for quality merchandise. During the war period we could not get quality

merchandise; we were forced to take whatever was available. That picture is rapidly changing. Inferior materials and workmanship are no longer acceptable. As a distributor, I am particularly interested in our sources adopting quality control techniques, because I am a firm believer in quality control being started in the purchasing of the merchandise rather than upon its receipt at destination. If we are going to rely upon preventing poor quality merchandise going out after it has been bought, or catching defects after the merchandise arrives at our plant, it will not only be extremely expensive, but in the end, the customer will be receiving unsatisfactory merchandise.

Before we buy merchandise we set up rigid specifications as to construction, quality, materials, and workmanship. Our primary concern is to have standards our customers desire and need. Our secondary concern is to have specifications which can be met economically.

During the war period, buyers in general became procurers and not really merchants or buyers. During the past five years while we have been in a sellers' market, the buyers did not know how to buy to specification. As a result, the Quality Control Department assumed the responsibility of training and educating the buyer to an understanding of exactly what specification buying means. It means not only specifying the grade of material to be used, but specifying every part that goes into making the garment or product, and more important, knowing the wearing qualities of each part. As an example, in developing specifications for a shoe, we do not specify merely the upper leather and sole leather, but state specifically the grade upper leather and whose tannage, also the grade sole leather as to quality and weight, and the tanner. The same thing applies to the counter, box toe, both quarter and vamp linings, and all the way down to the quality of thread to be used.

The average buyer does not take the time to dig into the developments of these specifications without the close supervision of the Quality Control Department. Hence, this department has assumed the full responsibility for seeing that the buyers not only develop these specifications, but live up to them in the pruchasing of merchandise.

As a company, we'd like to buy from manufacturers that use statistical quality control. Their control charts would reflect a picture of the process or conditions under which their products are made, give us an insight into the quality we could expect, and indicate how much further inspecting and examining we'd have to do in our own plant.

I therefore consider it the No. 1 responsibility of the Quality Control Department to see that all buyers or purchasers receive adequate reports on their manufacturers, showing the rejects for various reasons by manufacturers. The buyer in turn should make a report to the control department advising what action has been taken. The control department even goes a step farther. If we are buying a shirt from Jim Brown at $24.00 a dozen and the same shirt from Tom Jones at $23.50, and in our opinion the $24.00 shirt comes in better, does not need examining, and the workmanship in general is better, we make definite recommendations to the buying office showing that it is

cheaper for the buyer to purchase the $24.00 shirt, because the cost of examination is in excess of the extra 50¢ dozen and, more important, the workmanship and quality are far superior in the $24.00 shirt.

In other words, the Quality Control Department assumes part of the responsibility for the purchase of merchandise. Although they do not have the responsibility for the control of sources, they play an important part in advising the buyer what sources to buy from, and what sources we would like to do more business with. I am firmly convinced that once we get buyers to believe in specification buying, and to understand the true meaning of quality, they will have to buy from better sources who will give better workmanship at approximately the the same cost.

Aldens spends thousands of dollars annually to inspect incoming merchandise. Naturally, we do not want to have to inspect every piece of merchandise we receive. At the present time we are forced to decide just what amount, from each manufacturer, we must inspect to be assured that we pass on good quality to our customers. Merchandise that arrives at a plant with many defects is the first ear-mark of poor quality material as well as poor workmanship in the manufacturing of the garment. The place to start is to see that the buyers and the Quality Control Department have the same concept of quality. We have found that many times our examiners are expecting Double-A quality from a source of supply, whereas the buyer is willing to accept B quality, with the result that when the merchandise really comes in the way he bought it, the examining department decides it is not good quality merchandise, the workmanship is inferior, or for that matter, the material would not give service, and rejects the greater portion of the shipment. This causes bad source relations, causes a company to be criticized in the market, and in the end the buyer and the seller are unhappy over the deal. If we could be assured that our sources were using scientific quality control, and our buyers understood it, from there on we could direct a standardized procedure, which would eliminate 100% examination, and to a great extent the pitfalls of poor or misguided judgment.

As I mentioned, we are in the process of classifying all of our suppliers, and have been aided by the standard sampling techniques recommended by the quality control program. I know we'd prefer to do business with manufacturers that have adopted quality control, because it would reduce our rejects, customer returns, and the cost of a high percentage of examining. The Quality Control Department is always striving to cut costs in examining merchandise, and is spending this saving on the original cost of the goods, so that we can receive a better product which in turn assures our customers of receiving better merchandise. As we detect, through the sampling technique, manufacturer's errors and irregularities, they will be duly notified. If in a comparatively short time, we do not notice marked improvement, management will decide to drop the source. Before such a drastic step is taken we will strongly recommend that our manufacturers adopt the techniques of Quality Control by statistical methods.

I would never care to recommend a management tool unless I had experimented with it myself. About two and one-half years ago, we

instigated a quality control program. Our original object was to control and fight order filling errors that affected the customer. In a plant of our size, stocked with thousands of items of merchandise, operating and human errors are bound to occur. It is not uncommon for an employee to select a dress from a bin marked size 16 instead of from one marked 18. Prepackers are apt to tie together 4 washcloths instead of 3. An order filler could misread a 5 for an 8, and hence pick an entirely different item than the one the customer ordered. For years we have had a checking operation, which during the war period was not adequate or fool-proof. To control errors and isolate our trouble, we set up a sampling plan or a rechecking operation wherein we inspected work units in lots of 100. These work units were selected at random just as the merchandise was about to go to the Shipping Room. The errors found in the sample were immediately posted on a control chart. Although the program was started in a department we thought was doing a good job, we were somewhat surprised to find we were making about 3 errors per 100 units. Furthermore, a statistical analysis of the data revealed we held consistently at a 3% level in that department. The department manager and his assistant began to study the errors to determine if the trouble was caused by inadequate training of personnel, the arrangement of stock in the bins, poor lighting, or whatnot. Upon analysis, it was found that by making certain minor changes, such as the retraining of one checker, and a slight improvement in one handling, the errors could be materially reduced. In fact, within two months, the error ratio dropped below 1%.

It might be assumed that a reduction in errors would mean a sacrifice of production efficiency. On the contrary, just the opposite occurred. Within a two month period the efficiency increased from 82% to 107%. If a control program has merit it should speed up production as well as improve quality.

The presence of the control chart has a stimulating effect on management, supervision, and employees. The chart very dramatically tells a story, indicates how a group is doing, and helps all to realize a better way means a better job. For years management has had accuracy records, and error reports, and has bent every effort to control and correct the performance of its workers. Unfortunately, these reports were put into desk drawers, but now, through quality control techniques they are dramatically and publicly displayed so that everyone can see at a glance what is happening at a time when the results have some meaning. Any member of management, or any employee, can quickly observe:

1. Whether inspections are being made daily.
2. How much inspection is going on.
3. The number of errors found in each 100 units.
4. The trend of the errors.

To all, the control chart is a graphic reminder that quality is an ever-present problem that needs constant attention. Our employees, supervisors, and Department Managers like the program. The individual worker knows what is expected of him and how he is progressing.

We have expanded our endeavors, and at the present time use it in 23 departments, including the office clerical activities, Shipping Room, and Billing departments. In the particular customer adjustments that troubled us, by means of statistical quality control, we were able to reduce our errors 25.4% over 1945, in the ratio of the number of adjustments to the number of orders shipped. Now that we are well into our 1947 Spring Season, all indications point to further improvements.

We intend to expand the program into other branches of our business. It is not mere crystal-gazing to say that I can foresee the potentials of this program in analyzing sales. It should help us to estimate more accurately the kind, type, and quality of merchandise our customers want. Two of our catalog production executives are investigating the possibilities of using quality control techniques in helping to set up specifications for our printing sources. We are eager to definitize the quality of printing and color which we feel is acceptable for use in the 24,000,000 catalogs we issue each year.

Along with our all-out effort to buy merchandise that is built to our specifications, we feel that statistical quality control will assist us in the standardization of our merchandise and our examining methods, and will aid us in setting limits and standards of performance for our sources.

I am extremely optimistic about the future, as there are signs that the American consumer will at last be guaranteed not only quality but service. I speak for Aldens when I say we shall make every effort to get and keep satisfied customers. They are the foundation of our business, and without them we cannot continue to grow. Our customers are our bread and butter, and we are grateful to any scientific methods of operation which help us to sell better merchandise better.

GENERAL INTRODUCTION OF CONTROL CHART PRINCIPLES IN INDUSTRIAL APPLICATIONS

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What is Statistics? Our object in this series of five clinics will be to try to give you a clear idea of just what this new tool, statistical quality control, is and how it operates. We want to show you why it can be expected to help you in your own plant to save money and to make a better product. Yours is a strange company if statistical control has nothing to offer you.

First let us look at this word "statistics". It is hard to pronounce and is in bad repute for other reasons. One of these is that it sounds like musty dry figures and complicated formulas. Another is for the same reason that it has been said "Some persons use statistics like a drunk uses a lamp-post -- that is, for support, not illumination," Let us scotch these two snakes at once. In the first place the "complicated mathematics" needed for statistical quality control are addition, subtraction, multiplication and division of simple numbers, with an occasional square root thrown in to keep you from thinking you are getting something for nothing. Moreover, if you think statistics in the form of a control chart is dry, make one and see how much interest it stirs up in the shop. As for the second main objection, it must be admitted that many persons are interested only in gathering facts and twisting them to prove any desired conclusion which they were "sure" of in the first place. The smart business executive no longer says, "Paul, go out and get me facts to prove that alloy, X-3, is the best for our use." Asked this way, Paul can "prove anything." Instead, the modern executive says, "Paul, compare these alloys until you have what evidence you need to make a safe decision." It is "Let's get at the facts," not "I know this is so, but I want to convince the board." The sound executive must be interested in following out the truth wherever it leads, if he and his company are to succeed against competition.

Just what is statistical data? In essence, statistical data are numerical results that vary, from piece to piece, measurement to measurement. No matter how hard we try, we can never make two things exactly alike. Modern ingenuity can make them almost alike but if we measure accurately enough there will be a difference, if not to the nearest hundredth or thousandth of an inch, then to the nearest ten-thousandth or hundred-thousandth. In fact, in precise work, consecutive measurements of the same piece in the same place will vary. Wherever such variations occur we have statistical data.

It may well be asked why statistical methods are becoming more important in industry. I think the reasons are first that statistical methodology has been improved by many, especially Walter A. Shewhart, of Bell Telephone Laboratories, whose development of the control chart was of utmost importance. A second reason is that ever finer tolerances are being required for a higher precision product, to fully utilize the new contributions of science. Machines and production processes have greatly improved, as have measuring devices. The more precise we try to be the more important become the random variations from case to case. Statistical methods are primarily devised for just such situations.

Looked at in this way, we can say that whether you know it or not, whether you like it or not, inspection data, laboratory data, research data, production data, test data are statistical. If you are going to get the maximum benefit out of them you ought to know something about available statistical tools. You want to get everything out of your data that is there, and you want to avoid getting out things that are not there. Statistical methods are the sharpest tools for helping get the answers to such questions as: Which process is better? Are we getting all we can out of this machine? Is the less expensive formula adequate? Can we economically meet specifications? Is it safe to reduce inspection? Shall we accept the lot of incoming material? What is causing erratic performance?

As this series of lectures proceeds we hope it will become clear to you how these methods do apply to such questions. Since the techniques are just about universally applicable to all types of products and processes you are urged to keep your own production problems in mind as we progress and to try to see how the methods will help. Just have confidence that they can help and keep your eyes open for applications.

What is a Control Chart? Briefly, a control chart is a device for interpreting the meaning of the fluctuations in a series of numbers and for determining when to take action and when it will be a waste of time. Variations in quality are shown graphically by a series of points. When thinking of quality measures you must think of them in the broadest possible terms. Not only may a control chart be made for a series of numbers, such as dimensions, electrical measurements, physical properties, chemical analyses, per cent of defective pieces, uniformity of performance, life test data, weights of loading and visual defects, but also of such numbers as daily production, unit costs, efficiency ratios, absenteeism, accident rates, time-study figures and labor turnover. Even golf or bowling scores may be used.

Having a series of varying numerical results which we wish to study, what would be more natural than to plot a running record of performance? Along the vertial scale would be plotted the quality measure and along the horizontal scale would be shown the time of occurrence or other identification of the point. Figure 1 shows three graphs of this type. In these charts each single point represents the quality performance for a sample of several pieces or measurements. Such a sample gives the point a better chance to represent more accurately the conditions obtaining while those few pieces were being produced and inspected. Thus in Figure 1 (a), each single point shows the average tensile strength for five pieces and thereby gives a picture of the "average" strength. The quality characteristic in chart (b) is variability, as measured by the range, the difference between the lowest and the highest among four blast furnace carbon analyses. When the analyses are consistent the range will be low, and when the analyses are scattered the range will be large. Graph (c) shows the per cent of pieces failing on the "D" test, for each day in August. Each graph shows in its own way something about the quality of product. Average strength is crucial, consistency of analytical results must be watched closely, and per cent of units proving defective is something with which management is always concerned. Which of these graphs do you think shows "control"?

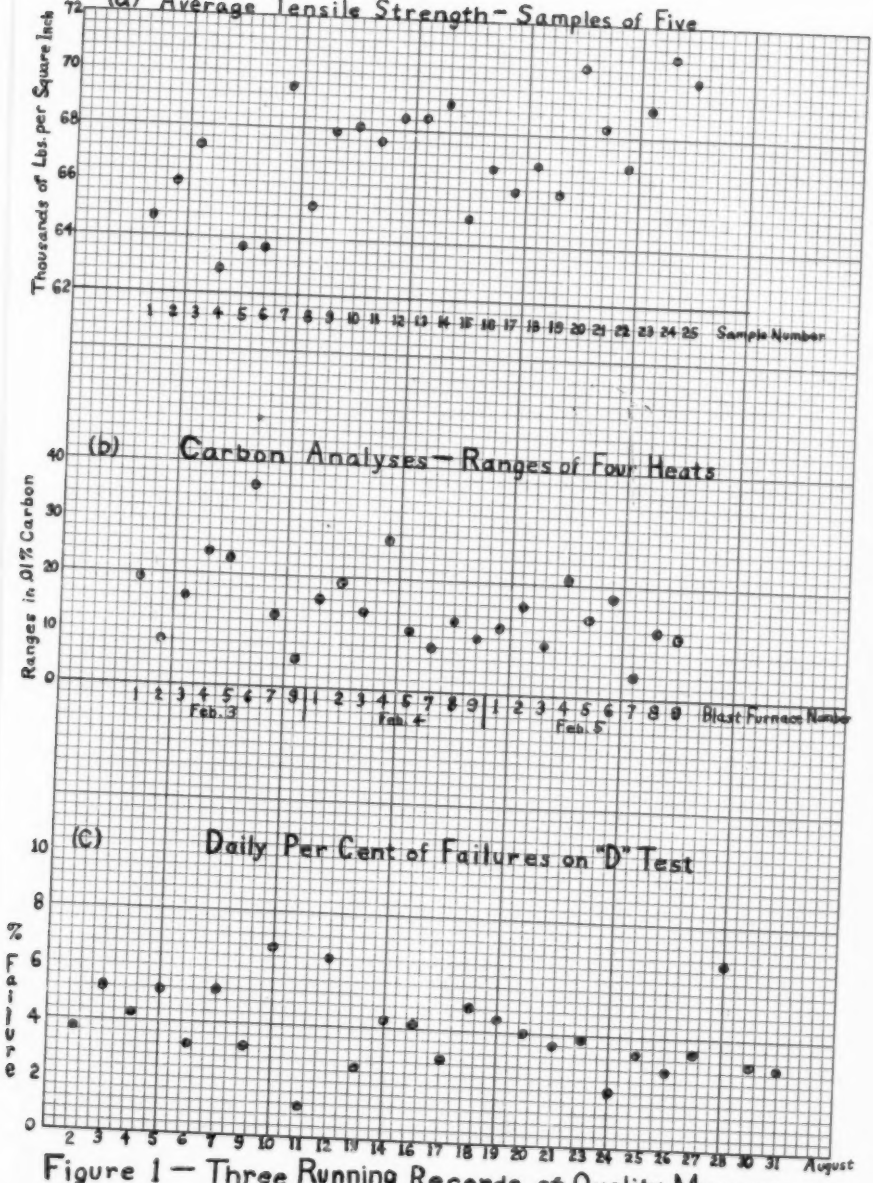
(a) Average Tensile Strength – Samples of Five
Thousands of Lbs. per Square Inch
72
70
68
66
64
62
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Sample Number
(b) Carbon Analyses – Ranges of Four Heats
Ranges in 01% Carbon
40
30
20
10
0
1 2 3 4 5 6 7 9 1 2 3 4 5 7 8 9 1 2 3 4 5 6 7 8 9
Feb. 3
Feb. 4
Feb. 5
Blast Furnace Number
(c) Daily Per Cent of Failures on "D" Test
% Failure
10
8
6
4
2
0
2 3 4 5 6 7 9 10 11 12 13 14 16 17 18 19 20 21 23 24 25 26 27 28 30 31
August

Figure 1 – Three Running Records of Quality Measures

Now note carefully the following points. In all three cases the quality level varies from sample to sample (point to point). This will be true even though we make every effort to hold all conditions just as alike as is humanly possible. There will always be some "natural variability" in each of these quality characteristics. On the other hand, unusual performance calls for action. If tensile strength is exceptionally weak, investigation must be instantly taken to find the cause and remedy it and probably to check the recently produced product. Exceptionally high tensile strength might just be due to poor testing or there might be some identifiable reason for better strength and we want to learn how to keep on producing this better quality product for the future. Excessive inconsistency of analyses, as evidenced by a large range within a single sample, would be cause for serious search for the reason. In chart (c) excessively high or low per cent defective figures would demand action analogous to that in the two possibilities for chart (a).

What is Unusual Performance? This is often a most difficult question to answer. If samples are small, considerable variability is to be expected. In such a case a rather large variation in quality performance which may look to the eye like a sure evidence of "something slipping" may be only what one should expect from the "natural variability" inherent in the process. On the other hand if the samples are large then an insignificant appearing variation in quality level may be indicative of some "bug" in the process which should be found and isolated. As an example of the foregoing see Figure 2. Chart (a) is in statistical control while chart (b) is not, even though the fluctuations in the latter are less great. This is largely because of the difference in sample size.

Even choice of scale alone can make a great difference to the reader. See Figure 3 in which the same data are plotted on two different scales. One would scarcely hesitate to call one in control and the other not unless he knew they were the same data. Practical and commonly occurring examples of human fallibility in judging the meaning of variations in product are (1) too frequent adjustment and resetting of machines or process when still running satisfactory; (2) adjusting in the wrong direction; (3) looking for trouble when the process is really doing all that can be expected of it; (4) failing to notice a seemingly slight excessive fluctuation which should be the tip-off to impending serious trouble.

A statistical control chart adds to such charts as those in Figure 1, three lines which greatly aid in interpreting variations in quality. There is first the central line to show what the average performance is. It is a sort of reference line or par, and tells us what is usual or to be expected. The points tend to vary around this line. The key contribution of the control chart, however, is the pair of "control limit lines". These two lines give a band around the central line which greatly facilitates the interpretation of variations in quality. These lines help us to distinguish between two quite different kinds of causes of variation:

1. Random causes - the whole host of influences, the effect of each of which is very slight, but whose total effect is what

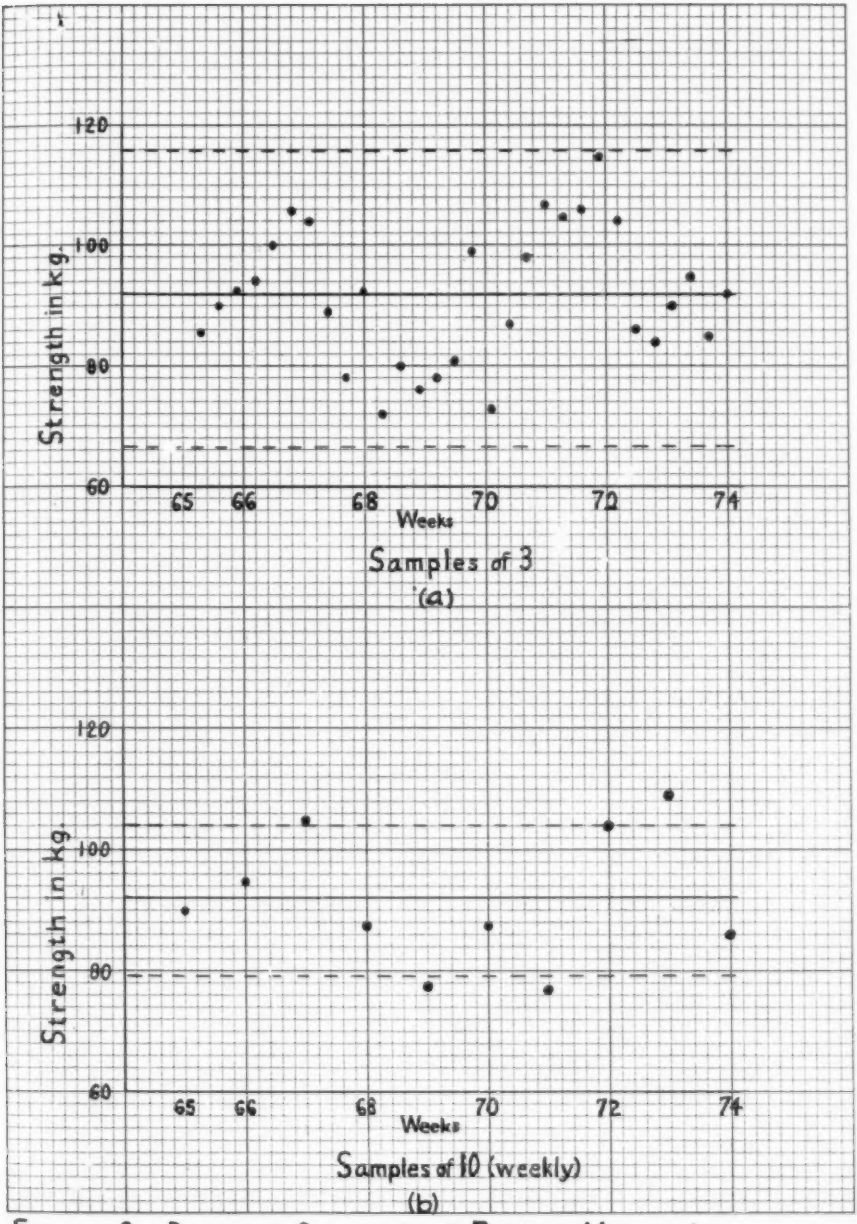

Figure 2 – Breaking Strength of Roofing Material

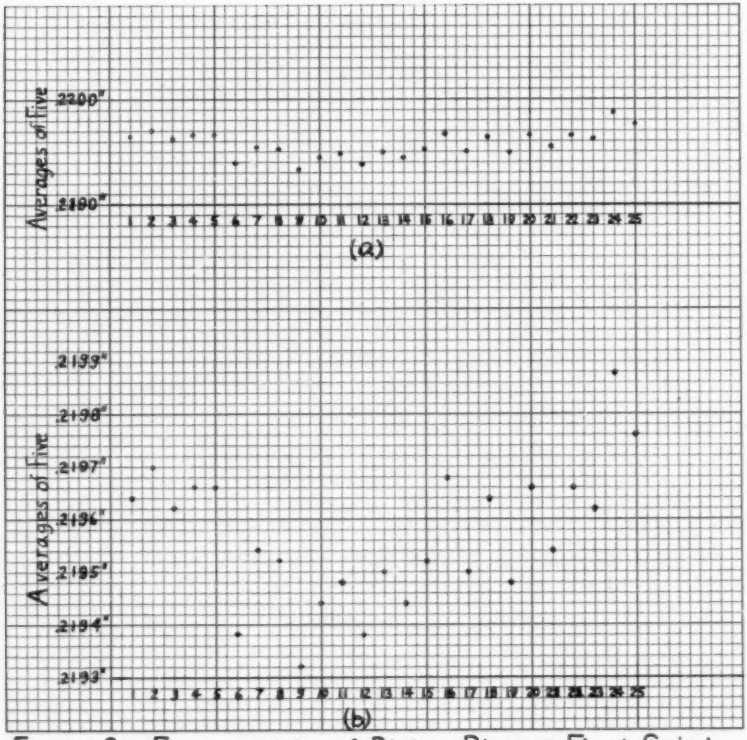

Figure 3 - Edge-widths of Piston Rings - First Grind

we call the "natural variability" of the process. It is not worth our while trying to track down one of these random causes; it is like hunting a needle in a haystack without benefit of a magnet.

2. Assignable causes - significant changes in the manufacturing process, such as use of a wrong formula, work by a new, poorly-trained operator, a cracked bearing, new bar stock, change in melting practice, dull tool, excessive hardness in castings and a let down in standards by the inspection staff. Usually there are but few assignable causes at work at any one time, but each one has a considerable effect on product quality, and it most certainly is desirable and feasible to isolate and eliminate such causes.

Let us now show what the meaning of the control band is by reference to Figure 4, which is merely Figure 1 with central lines and control limits drawn in, as a result of the type of calculations which will be discussed in the second and third lectures of this series. Points which lie outside the control band are a clear-cut indication that an assignable cause was present while the pieces or material for that sample were being produced and tested. One should immediately try to

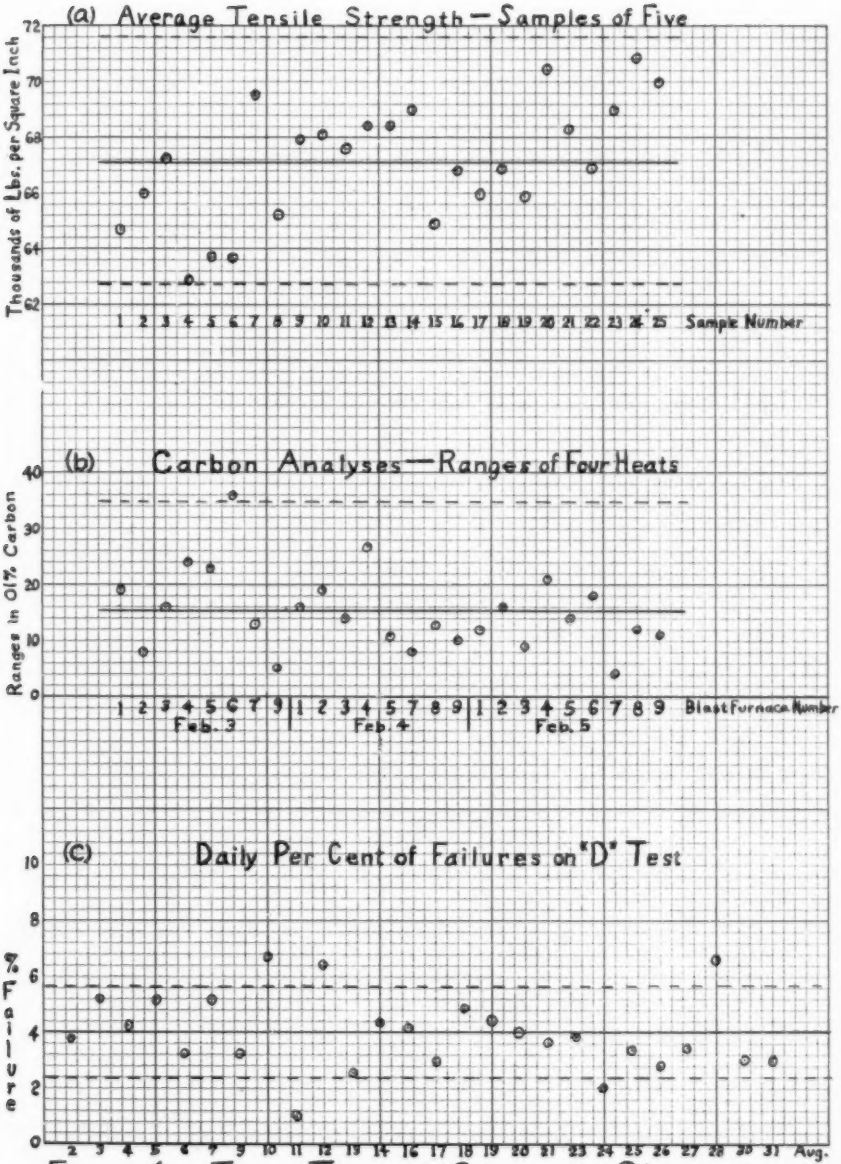
(a) Average Tensile Strength — Samples of Five
Thousands of Lbs. per Square Inch
72
70
68
66
64
62
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 Sample Number
(b) Carbon Analyses — Ranges of Four Heats
Ranges in 01% Carbon
40
30
20
10
0
1 2 3 4 5 6 7 9 1 2 3 4 5 7 8 9 1 2 3 4 5 6 7 8 9 Blast Furnace Number
Feb. 3
Feb. 4
Feb. 5
(c) Daily Per Cent of Failures on "D" Test
Per Cent Failures
10
8
6
4
2
0
2 3 4 5 6 7 9 10 11 12 13 14 16 17 18 19 20 21 23 24 25 26 27 28 30 31 Aug.

Figure 4 - Three Typical Control Charts

find out what was different or unusual at that time as compared with other times or conditions. By looking for any changes in the manufacturing and testing process at the time and place at which that sample occurred, one can usually find the assignable cause of the change in performance and proceed accordingly.

In graph (a) of Figure 4, we see that all points lie within the control band. Hence our conclusion is that what fluctuations there are in tensile strength are no more than what we should expect from our process. There is no point in seeking an assignable cause for the low tensile of sample 4 nor for the high tensile of sample 20. Such fluctuations can perfectly well have come from the same stable production process. The process back of these results can be given a "clean bill of health".

In chart (b) of Figure 4, we find one point outside of the control limit, that for the four heats of February 6. Thus we can say with much confidence that there is a reason for such a great extreme fluctuation among the four heats as .36%. We can seek for the reason with confidence that there really was something at work then.

To the untrained eye the original graph (c) of Figure 1 seems to show the best control of the three. We see in graph (c) of Figure 4, however, that there are three points out on the high side and two out on the low side. There was almost certainly an assignable cause at work on all five of these days. Study of the conditions on these days is clearly indicated as a fruitful occupation. The reason for the bad quality on August 10, 12 and 28 should be determined and such conditions eliminated. If you want to hear a beautiful blow-up, however, just start telling the production man that he was "out of control" on August 11 and on August 24. You will have plenty of explaining to do. The better approach (after making sure that the cause for the low per cent failure is not just lax inspection) is to say "What was different on August 11 that gave us such a swell product? We want to do that same way in the future." Finding assignable causes for both bad and good performance did pay off here because, from July 1 to mid-September, the average per cent failure dropped from 5.5% to 1.5%.

Why Does the Control Chart Work? The statistical control chart, as developed by Walter A. Shewhart, is based upon the laws of probability and sampling theory. Because all variation and random causes tend to follow rather definite patterns, it is possible to use the same kind of control chart calculation for any set of results which are subject to random fluctuation. The theory supplies us with simple rules for calculating control limits such that if the process really is stable, then only very rarely will a point go outside the control limits. It will take a rare "ganging up" of random causes to contribute a point outside the control band. This being so and industrial processes being as "cussed" and apt to go "sour" as they are, is it not an awfully good bet that something really slipped when a point shows out, rather than that it is just "chance" at work and everything was still all right? Abundant industrial experience shows the wisdom of betting on that side.

Now on the other hand, if a point lies inside the control band, then on the whole we have insufficient evidence that anything other than chance causes was at work. Whatever fluctuation is indicated by such a point can easily arise by chance alone. We are quite likely to be wasting our time looking for the cause, for too often there is nothing really at work.

There are two general kinds of mistakes one can make. As a practical man you can go out to the machine and try to find what is causing a change in quality level when the whole process has not changed at all, that is, there is no assignable cause at work. On the other hand, you can fail to notice the presence of an assignable cause which is going to give a lot of future trouble. In brief, you can look for an assignable cause when none is present, or fail to look when one is. Use of a control chart will not guarantee that you will make neither mistake. It will, however, help very materially. The control limits have been set at an economic balance between these two errors. If the limit lines were set much farther apart in practice, we should too seldom be looking for assignable causes, when present, even though we should very seldom indeed be making the mistake of looking for an assignable cause when none is present. If the control limits were to be pulled in closer, then we should more often make the mistake of looking for an assignable cause when none was present, but we should very seldom fail to note the presence of an assignable cause when one actually was at work. The control charts as they are set give a good balance between these two potential errors. That it is an economical balance is attested by the spectacular record of savings accomplished both in wartime and in peace and in all types of industries.

Can I Use Control Charts in My Plant? If you have such a thing as random variability in your plant you can. And if you are trying to do a precise job in any kind of manufacturing, you are bound to encounter random errors. The more precisely you try to measure or to produce, the more you will be concerned with and bothered by random causes. Not only will chance causes become more important if we have been holding tolerances of plus and minus a ten-thousandth of an inch and want to cut this to plus and minus half a tenth, but it will also be true if we have had tolerances of plus and minus two inches and want to cut this to plus and minus one inch.

It is primarily because industry has been trying to do an ever better job on all types of products that statistics and the control chart have become so much more important. As further refinements are made you will all witness a great increase in the use of the control chart. You had better witness such an increase in your own plant or you are not going to be able to compete.

Personally, I can say that I am still looking for the product and the company which cannot profit by the use of statistical quality control.

What Kinds of Advantages Can Accrue From Control Charts? A number of potential advantages of the control chart may be listed as follows. No long discussion will be given here, since the fourth lecture in this series will be primarily concerned with applications, which you

will be in a better position to understand and profit from after hearing the second and third lectures in the series.

1. The control chart can save you time by saving you fruitless searching when no assignable cause is at work.

2. The control chart can help you track down assignable causes by careful sampling. It is a powerful tool to aid the production man and engineer find the "bugs".

3. A control chart can tell you when a process is doing all that can be expected of it. A careful file of past performances of your machines can tell which machine to put on a new job.

4. Since a process, when in statistical control, can be relied upon, one can often drastically cut the amount of inspection with adequate assurance of meeting standards. On the other hand, little confidence can be placed on a machine or process which is not in statistical control. It is not stable and the product may require a large amount of inspection for quality assurance.

5. A control chart program can enable you to spend most effectively inspection and supervision time. Instead of spending about the same amount of inspection and checking on all similar processes and products, you can spend a lot more on the less reliable, and safely spend a lot less time on those you can trust.

6. By eliminating assignable causes the variability in the product is often drastically cut. Until substantially all assignable causes have been eliminated from a process, you just do not know how good a job it can do.

7. Control charts can greatly aid design by giving them an accurate picture of what each process can do. Request for change of a specification is most justifiable if a record of control has shown the process is doing all it can.

8. One of the most common advantages of control charts has been large savings in scrap and rework, through elimination of assignable causes of rejects.

9. Control charts can enable you to back your product more confidently through getting production processes in control. They can improve producer-consumer relations.

10. Sample sizes can be set scientifically so that adequate protection is obtained on a minimum of inspection.

11. Control charts are a way to get at the facts. They can help you decide disputes on the basis of facts. Factual data help on meeting customer complaints.

12. Warning can be had of impending trouble, often-times much before "commonsense" will have noticed any change in conditions.

13. An intangible but a most important advantage is that a control chart program will often be the means of getting a whole plant more quality-minded.

Statistical Quality Control is Only a Tool. Lest you be left with the impression that I think that the above potential advantages are a sure accompaniment of the installation of a control chart program, let me here say that statistical quality control is no panacea for all the ills of manufacturing. It is only a tool, although it is a sharp tool. In the proper hands, advantages such as those above will accrue. In the wrong hands, nothing constructive will be accomplished. An experienced cabinet maker could make a beautiful piece of furniture with little more than a saw, screw driver, hammer and plane, whereas many a person with all the tools in a Sear's catalogue would still make something technically known as a "botch". It is largely a question of imagination. A man who knows his product and the manufacturing process and has some imagination will find in control charts a tool of great potentiality.

MEASUREMENT CHARTS IN QUALITY CONTROL

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The Shewhart Control Charts, which are so central to statistical quality control work, are of two general types: (1) measurement charts, and (2) attribute charts. In this session we shall come to grips with some of the essential details that go with making and using measurement charts. These charts are also called "variables charts", but they are most commonly referred to simply as $\bar{X}$ and R, or "average" and "range" charts. They are the appropriate control charts when the quality characteristic under study is something that can be measured. Thus, if it is desired to control a dimension, a weight, electrical resistance, tensile strength, hardness, time-of-blow for a fuse, percent concentration, and so on, the $\bar{X}$ and R charts would be correct charts to keep.

Getting the data. We can't build a brick house without bricks, nor can we keep a control chart without data. It follows that we must first decide what data we need, how we shall gather and record it, and the amount of data we will need. An $\bar{X}$ and R chart can be kept for only one kind of measurement at a time. Thus, if it is desired to control an outside diameter and a length on a given piece, it will be necessary to keep a separate $\bar{X}$ and R chart for each dimension.

To make matters more concrete, suppose we consider one of the intermediate steps in a sequence of operations which begins with a rough valve forging and ends with the completed valve. The dimension covered by the particular operation we are studying in this sequence is the length of the valve from the seat to the tip of the stem. (See Figure 1.) The operation is performed on a screw machine fitted with a

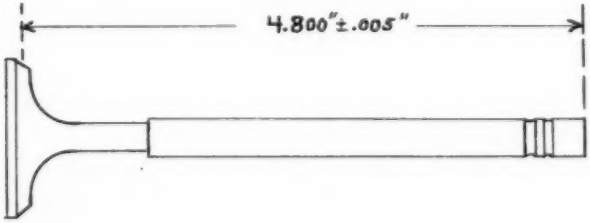


FIGURE 1 - Valve

fast loading fixture, but (at the time we begin to investigate it) depends to some extent also on the skill of the operator who moves the tool slide by hand. The quality characteristic under study is thus a length, so measurements of this length are the data we need. The control of this characteristic is important because the maintenance of accurate length at this stage of the sequence has an important hearing on subsequent operations.

The background for the example we are studying comes from a paper by E. F. Gibian in the September, 1946, issue of Industrial Quality Control. However, most of the details and data we shall use have been improvised to serve the purposes of this discussion, and it is not to be inferred that we are duplicating Gibian's paper. Incidentally, this paper in its entirety is one that every beginner in quality control ought to read. It was given as one of the clinic papers at the 1946 Midwest Quality Control Conference, and is an excellent example of a correct application of $\bar{X}$ and R charts to line production problems. Among other things, the paper illustrates the use of a separate $\bar{X}$ and R chart for each dimension studied.

Returning to the problem of getting data on this operation, let us decide to measure the seat-to-tip-of-stem length on a random sample of 5 pieces from current production at approximately every 20 minutes. In control chart work a large number of small samples gives a more sensitive reflection of process behavior than does a small number of large samples. Samples of 4 or 5 are generally preferred in most applications. We choose the size 5 because of its arithmetic convenience. We shall purposely avoid an inspection visit at exactly every 20 minutes; such punctuality raises a psychological hazard for the operator against which we can protect him by making our inspection visit somewhat more casual. Finally, we shall here take for granted the accuracy and reliability of the instrument with which the measurements are made, and the competency of the inspector who makes the measurements. It will pay to check these assumptions frequently in an actual application. Never convict a process until you are sure the evidence, i.e., the data, is adequate and accurate.

Shall we "grab" 5 pieces from the tote pan, or take 5 pieces as they come off the machine when we make an inspection visit? An adequate discussion of the respective merits of these two ways for taking the inspection sample would use more time than we can give to it here. For our purposes, it will suffice if each time we visit the process we take 5 pieces at random from among those produced since the last inspection. A good discussion of how to take the sample will be found on pp. 181-183 of Ref. 1.

How many samples shall we take before we begin to summarize results? We want the process to tell us what it is doing as quickly as possible, but we don't want to pass judgment on it without giving it a decent chance to present its case. If it is a fast process, we can get evidence quickly, and so we can afford to get more evidence before summarizing, unless, of course, it happens to be just a short run. The short run problem in quality control is a story all its own; we cannot take time to go into it here except to say that there are ways to deal with it statistically. On this point, see Ref. 1, pp. 500-501 and Ref. 2, pp. 150-157. However, if getting the inspection data is expensive and/or time consuming, we want to be able to summarize results from the minimum amount of evidence consistent with good statistical theory. A good working rule is: never fewer than 50 individual measurements if at all feasible, and preferably 100 or more. For our problem, 20 samples of 5 measurements each will give 100 readings, and will cover just about one day's production at the rate of about 3 inspection visits per hour.

How shall we record the data? We need a record sheet that will be both meaningful and efficient. It must provide three essentials: (1) adequate identification, (2) convenient provisions for recording observed data, and (3) space for special comments or remarks concerning certain details that may need to be noted to make the data completely informative. At each inspection visit we are going to record 5 measurements, their average, and the difference between the largest and smallest of the 5 readings, i.e., their range. If we suppose that the specification for seat-to-tip-of-stem length is 4.800" ± .005", we shall find it more convenient to record the measurements in units of .001" above and below 4.800" as the zero point than to clutter up the data sheet with the actual measurements. Figure 2 shows a form of record sheet which is rather widely used. Other forms less compact, but providing more detail, may be found in Ref. 1, p.172, and Ref. 3, p. 23. We shall adopt the form shown in Figure 2 as our standard.

Making the charts. Now that we have the data, how do we make the charts? We can make three different charts from these data: (1) an X (or individuals) chart, (2) an $\bar{X}$ (or average) chart, and (3) an R (or range) chart. The average and range charts are the ones most widely used in quality control work, and the ones with which we shall be mainly concerned. However, X charts are used in some plants, and they do provide convincing graphical evidence of the folly of making resettings of a machine on the evidence given by a measurement on just one piece from the process. We shall begin the construction of all three types, but go on to complete and discuss only the average and range charts.

First, lay off a horizontal, sample identification scale along the bottom of the paper. It will be numbered from 0 through 20 for our data. Then lay off a vertical scale at the left separated into three parts. The lower portion of this vertical axis is reserved for ranges, and is scaled from zero through 10 for our data. The middle portion is reserved for averages, and is scaled from -2 through 9, reading from bottom to top, for our data. The upper portion is reserved for individual measurements, and is scaled from -3 through 15 for our data.

In the panel for individuals (X's), plot the 100 values of X by sample number; i.e., on the #1 sample line plot the 5 measurements 3-6-2-5-4 recorded on the data sheet of Figure 2. In the panel for averages ($\bar{X}$'s), plot the 20 values of $\bar{X}$ from the data sheet, and in the panel for ranges (R's), plot the corresponding 20 values of R. Don't hesitate to plot the points boldly -- there is no advantage in putting pin points on the chart — we want to be able to see the points! Moreover, if we plot the points boldly, and if we have chosen the horizontal and vertical scales wisely, it will not be necessary to connect the points. There is no harm in doing so; it is just a time-consuming, and therefore expensive, luxury to put these lines in, although it must be conceded that their presence on an average and range chart does "dress up" the chart.

Figure 3 shows this much of the job completed as described above. You have already been told that what we see here are not yet control charts. We proceed now to complete the construction for the averages and range charts.

Figure 2.

$\bar{X}$ and R CONTROL CHART DATA SHEET

Product Valve #E7714 — Machine Lathe #554

Characteristic Length - seat to tip of stem — Operator #B245

Unit of Measure .001" from nominal — Sample 5 per 20 min.

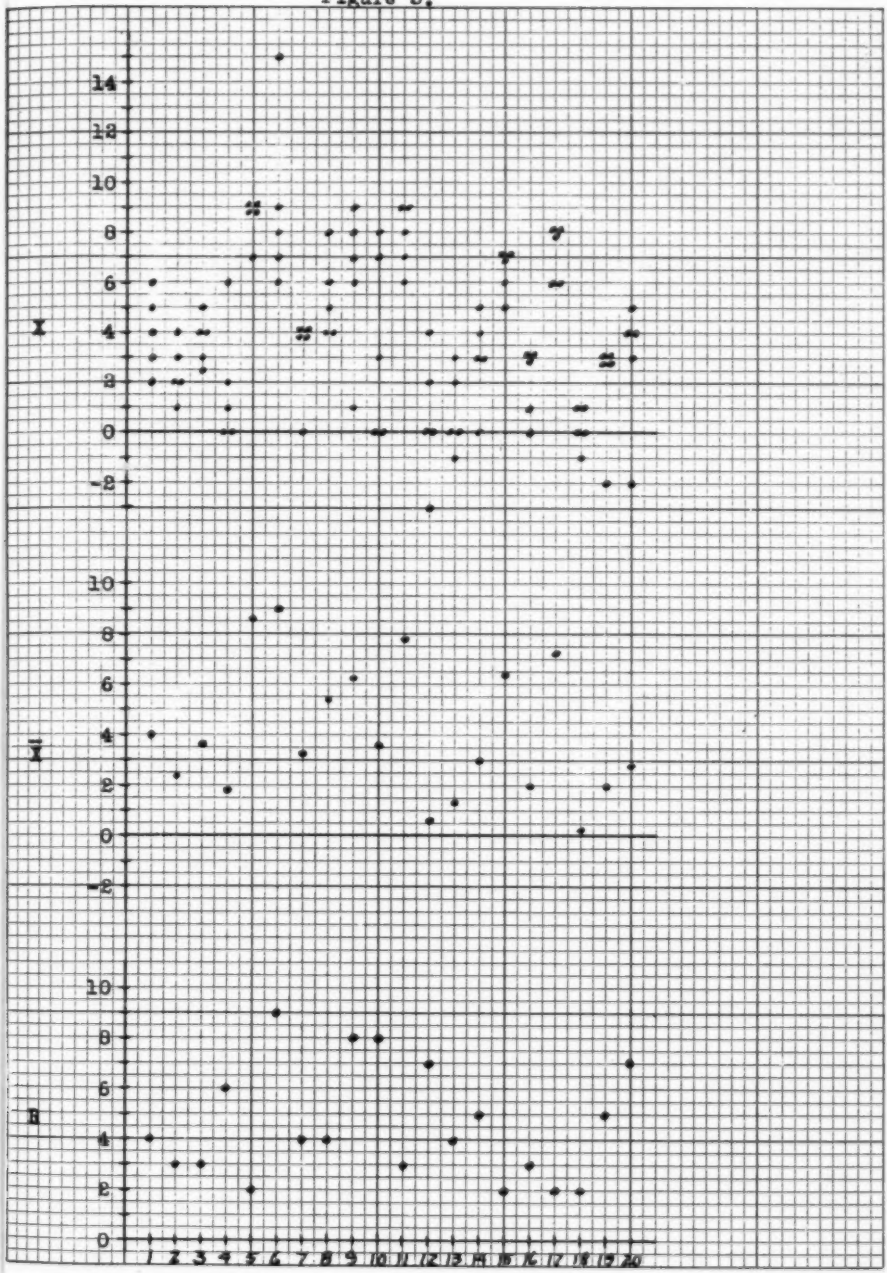
Specifications 4.800" ± 0.005" — Test Set #000

Operation Machine tip of stem — Order No. XXX — Dept. B2

Inspector John Doe

Sample No.	Date & Time	X_1	X_2	X_3	X_4	X_5	$\bar{X}$	R	Notes:
1	5/5/47 8 AM.	3	6	2	5	4	4.0	4	
2	8:20	2	1	4	3	2	2.4	3	
3	8:45	3	4	2	4	5	3.6	3	
4	9:15	0	1	6	0	2	1.8	6	
5	9:30	9	9	9	7	9	8.6	2	
6	9:50	15	8	9	7	6	9.0	9	
7	10:20	4	0	4	4	4	3.2	4	
8	10:45	5	6	4	8	4	5.4	4	
9	11:10	8	1	6	9	7	6.2	8	
10	11:30	7	0	3	0	8	3.6	8	
11	12:05	7	6	9	8	9	7.8	3	
12	1:30	4	0	-3	0	2	0.6	7	
13	1:50	2	-1	0	3	0	0.8	4	
14	2:15	3	5	0	4	3	3.0	5	
15	2:40	7	5	7	6	7	6.4	2	
16	3:00	3	1	0	3	3	2.0	3	
17	3:30	8	6	8	6	8	7.2	2	
18	3:45	0	1	1	-1	0	0.2	2	
19	4:10	3	3	-2	3	3	2.0	5	
20	4:40	4	-2	5	3	4	2.8	7	
					Totals		80.6	91	

Figure 3.


X
14
12
10
8
6
4
2
0
-2
$\bar{X}$
10
8
6
4
2
0
-2
R
10
8
6
4
2
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

First, we want to locate the center line, or average level of performance, on each chart. To do this, take the data sheet (Figure 2) and divide the total at the bottom of the $\bar{X}$ column by 20, because there are 20 values of $\bar{X}$ in this column. Since each of the entries in this column is an average, the result is an average of averages — a double average, if you wish, -- which we label appropriately $\bar{\bar{X}}$. It is, of course, the same number we would get if we totalled the 100 individual X values in the body of the table and divided this total by 100. Similarly, dividing the sum of the 20 values of R by 20, we get an average range value which we label $\bar{R}$.

In statistical quality control, any symbol which has a bar over it represents an average value for the variable characterized by the symbol. Also the word "total", which always involves adding a series of numbers, is abbreviated in statistics by the capital Greek letter sigma, Σ. Thus, if there are n values of X in a sample, then the average for that sample is given by the formula $\bar{X} = (\Sigma X)/n$. Applied to sample #1 of Figure 2 this becomes $\bar{X} = (3 + 6 + 2 + 5 + 4)/5 = 4.0$. It follows that if our data sheet contains N samples of n measurements each, and we wish to find the average of the N values of $\bar{X}$ and the N values of R, the formulas needed are $\bar{\bar{X}} = (\Sigma \bar{X})/N$ and $\bar{R} = (\Sigma R)/N$. For our data, these formulas yield $\bar{\bar{X}} = (80.6)/20 = 4.03$ and $\bar{R} = (91)/20 = 4.55$.

Finally, we need to locate the "control limits", or "action lines", that complete the chart and make it possible to tell whether the variation shown on the chart is random variation that can be tolerated, or erratic variation arising from assignable causes that call for investigation and corrective action. This is accomplished by using some numbers derived for this purpose by mathematical statisticians. These numbers depend on the size of the sample used (in our case 5), and are given for sample sizes running from 2 through 20 in Ref. 1, from 2 through 12 in Ref. 2, and from 2 through 15 in Ref. 3. You do not need to know how to derive these numbers in order to use them any more than you need to know how to build an automobile in order to drive it! But you better know the distinction between an accelerator and a brake pedal before you start anywhere in an automobile, and you better be sure you know what these various tabulated numbers are for before you go waving any control charts around the shop!

Just now we are concerned with what numbers to use and how to use them; later we shall consider more carefully what they mean. To locate the control lines on the average chart, we need the number denoted by A_2. For sample size n = 4, $A_2 = 0.729$, and for sample size n = 5, $A_2 = 0.577$. The number A_2 is used as a multiplier with the average range, $\bar{R}$. Thus, for our data, we have: $(A_2)\bar{R} = (0.577)(4.55) = 2.63$, after rounding the product to two decimal places. This number is then added to and subtracted from the center line value, $\bar{\bar{X}}$, to give the location of the control limits. Using $UCL_{\bar{X}}$ for "upper control limit on averages" and $LCL_{\bar{X}}$ for "lower control limit on averages", we have for our data.

$$UCL_{\bar{X}} = \bar{\bar{X}} + (A_2)\bar{R} = 4.03 + 2.63 = 6.66$$
$$LCL_{\bar{X}} = \bar{\bar{X}} - (A_2)\bar{R} = 4.03 - 2.63 = 1.40 .$$

To locate the control limits on the range chart, we need the numbers denoted by D_3 and D_4. For sample sizes n = 4 and 5 , $D_3 = 0$, and $D_4 = 2.282$ and 2.114 respectively. The numbers D_3 and D_4 are used as multipliers with $\bar{R}$ to give the control limit values for ranges directly; i.e., the products $(D_3)\bar{R}$ and $(D_4)\bar{R}$ do not need to be added to or subtracted from any number. Using UCL_R for "upper control limit on ranges" and LCL_R for "lower control limit on ranges", we have for our data

$$UCL_R = (D_4)\bar{R} = (2.114)\ (4.55) = 9.62$$
$$LCL_R = (D_3)\bar{R} = (0)\ (4.55) = 0\ .$$

The formulas and computations we have been discussing are summarized in Figure 4. We plot the center line $\bar{\bar{X}} = 4.03$ as a solid line on the

Figure 4.

ANALYSIS OF CONTROL CHART DATA IN FIGURE 2

$$\bar{\bar{X}} = \frac{\Sigma \bar{X}}{20} = \frac{80.6}{20} = 4.03 \qquad \begin{aligned} UCL_{\bar{X}} &= \bar{\bar{X}} + (A_2)\bar{R} = 4.03 + 2.63 = 6.66 \\ LCL_{\bar{X}} &= \bar{\bar{X}} - (A_2)\bar{R} = 4.03 - 2.63 = 1.40 \end{aligned}$$

$$\bar{R} = \frac{\Sigma R}{20} = \frac{91}{20} = 4.55 \qquad \begin{aligned} UCL_R &= (D_4)\bar{R} = 9.62 \\ LCL_R &= (D_3)\bar{R} = 0.00 \end{aligned}$$

$$(A_2)\bar{R} = (0.577)(4.55) = 2.63$$
$$(D_4)\bar{R} = (2.114)(4.55) = 9.62$$
$$(D_3)\bar{R} = (0.000)(4.55) = 0.00$$

chart for averages, the center line $\bar{R} = 4.55$ as a solid line on the chart for ranges, the control limits $UCL_{\bar{X}} = 6.66$ and $LCL_{\bar{X}} = 1.40$ as broken lines on the average chart, and the limit $UCL_R = 9.62$ as a broken line on the range chart. The limit $LCL_R = 0$ is not plotted on the range chart since it coincides with the horizontal axis of the chart. The completed chart is shown in Figure 5. Note the chart identification details. These must be sufficiently complete so that the chart is a self-contained unit of information. Note also that the value of each control limit is put on the chart where it can be seen, and that the space between the range and average chart is used to accommodate the value of $\bar{\bar{X}}$ and of $\bar{R}$.

Interpreting the chart. What do the charts tell us? A process is "in control" when all the points on the chart lie between the control limits. This process shows lack of control with respect to averages. Moreover, the chart confirms what we already knew: the process is being operated at too high a level. The chart tells us how high! It shows that the average length of the 100 pieces we measured is almost at the upper specification limit. The operator is working to the high side, preferring to risk reworks rather than scrap. But reworks cost money too, and, at least, slow down net production. We knew this

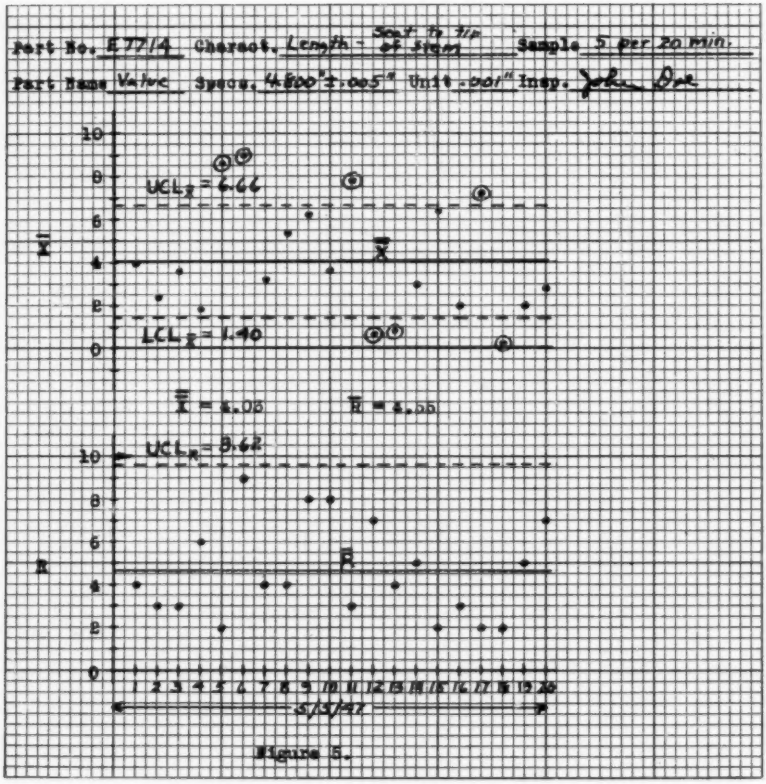

Part No. E7714 Charact. Length - Seat to Tip of Stem Sample 5 per 20 min.
Part Name Valve Specs. 4.600"±.005" Unit .001" Insp. Jake Doe
UCL x̄ = 6.66
LCL x̄ = 1.40
x̄̄ = 4.05
R̄ = 4.56
UCL R = 9.62
5/13/47

Figure 5.

process was unsatisfactory from the high proportion of reworks it had been making. That is why we put the chart on this machine: we wanted to get the facts, to see just how the process is behaving.

Points on an average chart show variation between samples; those on a range chart show variation within a sample. The ragged pattern of points on both the average and range charts in Figure 5 is evidence of lack of uniformity of performance on the part of both the machine and the operator in this process. However, all the points on the range chart are inside the upper control limit, so the range is in control. This is an encouraging sign, because it means that there is a "natural" tendency for this process to make lengths that will vary over a fixed "spread" from greatest to least if the operator will stop "hunting" for a correct adjustment in level. Apparently he is not setting the operation at a fixed level and then trying to hold to it: he is constantly attempting to "correct" the setting without sufficient evidence that it needs correction. The result of this "blind man's buff" is two-fold: (1) points fall outside the control limits on the average chart (7 out of 20 on this chart!), and (2) even though the range stays in control, it does so at a higher average range than would be the case if the operator could be taught to hold a setting and concentrate on improving his uniformity of operation.

Points outside the control limits call for corrective action; they are evidence of the presence of at least one assignable cause of erratic behavior not natural to the inherent capabilities of the process. It is a pretty safe bet in the case we are studying that the main "assignable cause" responsible for 7 points being outside the "natural spread" (the control limits) for averages is unwarranted "hunting" for adjustment on the part of the operator. However, good engineering judgment requires careful examination of the process, and a check-up of the testing equipment, to see if any mechanical errors can be found and improvements made that will help the operator hold to a setting. Good psychology requires that we emphasize this range chart to the operator: he stayed in control! Show him that he has the skill to do a better job, and that with the help of the chart, it should be possible to work more consistently to the blue-print mean.

Process vs product. It may have occurred to you that no blue-print limits were put on the average chart in Figure 5. One reason is that this is a chart for averages, whereas specifications refer to individual pieces. Of course, the range chart refers to individuals, but only with respect to the spread in individual dimensions, not the dimension itself. Beginners in quality control are prone to confuse control limits with specification limits, forgetting that the process doesn't care a hoot about specifications! The process only knows what it is doing with respect to level and spread. This is precisely the information we get the first time we slap a control chart on a process, and it is a mighty safe bet that the picture will not look like what design specifications had ordered the process to do!

The purpose of production is to make satisfactory product, but it is the process that makes the product, not the specifications. Therefore, the first objective in a control chart program is to get the process to operate in control. Follow through on the leads supplied by the chart, Find and eliminate the causes that send points outside control limits, or that lead to a too-high or too-low level of performance, or that are responsible for too great a spread in the process variation. This may be easy or difficult; it may take a little or a long time, but it must be done if what you want is a dependable process. A process operating in control is predictable; a process operating out of control is wholly unpredictable. Keep working on the process; ultimately you will know what the optimum capabilities of the process are. Once you have found out by control chart analysis the best the process can do for the money you can afford to spend on it, then you are in a position to ask "What kind of product will this process make?"

When you are ready to ask this question, what you will want is not just control, but satisfactory control. "Satisfactory" control means: (1) all points on the $\bar{X}$ and R charts between the control limits, and (2) process level and spread for individuals such that all pieces produced will meet specifications. This is your ultimate objective, and when it has been reached, you will be operating a process that can be counted on to make acceptable product.

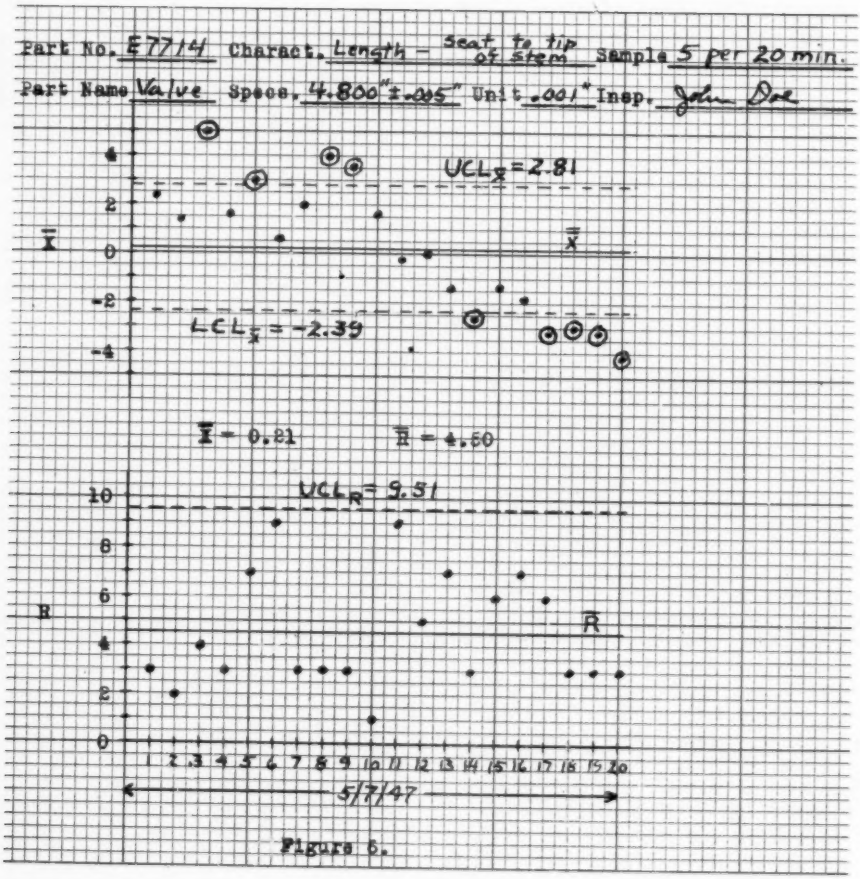

Part No. E7714 Charact. Length - Seat to tip of stem Sample 5 per 20 min.
Part Name Valve Specs. 4.800" ± .005" Unit .001" Inspr. John Doe
UCL$_{\bar{X}}$ = 2.81
LCL$_{\bar{X}}$ = -2.39
$\bar{\bar{X}}$ = 0.21
$\bar{R}$ = 4.60
UCL$_R$ = 9.51
5/7/47

Figure 6.

Figure 6 shows one of the later stages in the effort to bring the valve-length operation into control. It is possible to look at these charts and note (1) that process variability is still staying in control but at almost exactly the previous level ($\bar{R}$ = 4.55); (2) that the process is centered closer to the blue-print mean than formerly ($\bar{\bar{X}}$ = 0.21 vs 4.03); (3) that the process shows lack of control in averages (9 out of 20 points are outside control limits).

More careful analysis, however, reveals that during the production run covered by these 20 samples two distinct sets of conditions prevailed. Over the first half of this period (samples 1 - 10), the process was centered at a level of $\bar{\bar{X}}$ = 2.52 with an $\bar{R}$ = 3.80, which makes $UCL_{\bar{X}}$ = 4.71 , $LCL_{\bar{X}}$ = 0.33 , and UCL_R = 8.03 . Relative to these controls, one point (sample 3) was out on averages and one point (sample 6) was out on ranges. Over the last half of the period (samples 11 - 20), the process was centered at a level of $\bar{\bar{X}}$ = -2.1 with an $\bar{R}$ = 5.20, which makes $UCL_{\bar{X}}$ = 0.90 , $LCL_{\bar{X}}$ = -5.10 , and UCL_R = 10.99 .

Relative to these controls, both averages and ranges were in control. These figures may be checked by using the data of Table 1 and the formulas of Figure 4. Figure 7 shows this breakdown graphically.

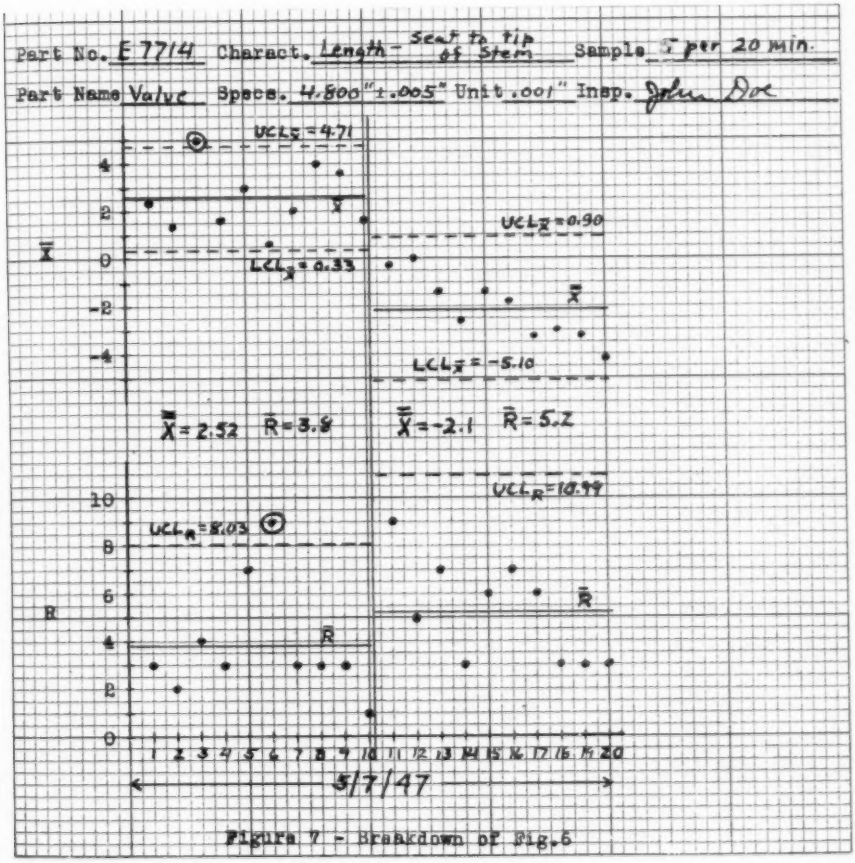

Part No. E 7714 Charact. Length - Seat to Tip of Stem Sample 5 per 20 min.
Part Name Valve Spece. 4.800" ±.005" Unit .001" Insp. John Doe
UCL$_{\bar{X}}$ = 4.71
LCL$_{\bar{X}}$ = 0.33
UCL$_{\bar{Z}}$ = 0.90
LCL$_{\bar{Z}}$ = -5.10
$\bar{\bar{X}}$ = 2.52 $\bar{R}$ = 3.8
$\bar{\bar{Z}}$ = -2.1 $\bar{R}$ = 5.2
UCL$_R$ = 8.03
UCL$_R$ = 10.99
5/7/47

Figure 7 - Breakdown of Fig. 6

Table 1.

$\bar{X}$	R
2.4	3
1.4	2
5.0	4
1.6	3
3.0	7
0.6	9
2.0	3
4.0	3
3.6	3
1.6	1
-0.2	9
0.0	5
-1.4	7
-2.6	3
-1.4	6
-1.8	7
-3.2	6
-3.0	3
-3.2	3
-4.2	3
4.2	90

Ten sample points (50 measurements) are, of course, a bare minimum to use as a basis for making inferences, but it is nevertheless safe to assert that Figure 6 reflects two different systems of chance causes rather than just one. A shift in level and dispersion as great as that observed here (Figure 7) could scarcely happen by chance, even with as few as ten samples.

The chart shown in Figure 6 calls for investigation and corrective action, not just because it shows lack of control on averages, but rather because it shows a distinct change in the pattern of process behavior. The investigation will probably reveal that over the first ten samples

(1) the process was set to operate at a level near 2.5;

(2) no adjustments in setting were made during this period;

(3) the operator, knowing he was still working on the high side, and instructed not to make adjustments on his own initiative, concentrated more of his attention on the manual portion of the operation, and, with two exceptions (samples 5 and 6), succeeded very well in reducing process variability, i.e., range.

Over the last ten samples, an investigation will probably reveal that

(1) some mechanical defect in the process caused it to operate at a progressively lower level;

(2) no adjustments in setting were made during this period;

(3) the operator, observing that the process was now operating on the low side of nominal, and being instructed not to make adjustments in setting, faced a psychological hazard which distracted his attention from the manual portion of the operation, and resulted in a definite increase in process variability ($\bar{R}$ = 5.2);

(4) the increase in $\bar{R}$ undoubtedly explains why all the last ten averages were in control, but even so, this increase in process spread, together with the low averages, almost certainly led to the production of some scrap toward the end of this run .

It is clear that the valve-length process has not yet attained a state of control, much less satisfactory control! More work must be done on it before we can depend on it to make acceptable product. The story implicit in Figures 6 and 7 suggests that with more experience in operating under control chart guidance, with further real engineering effort to discover how to make and hold a satisfactory setting for level, and with attention directed toward reduction in variability (range), there is good reason to believe that real improvement in this process is possible.

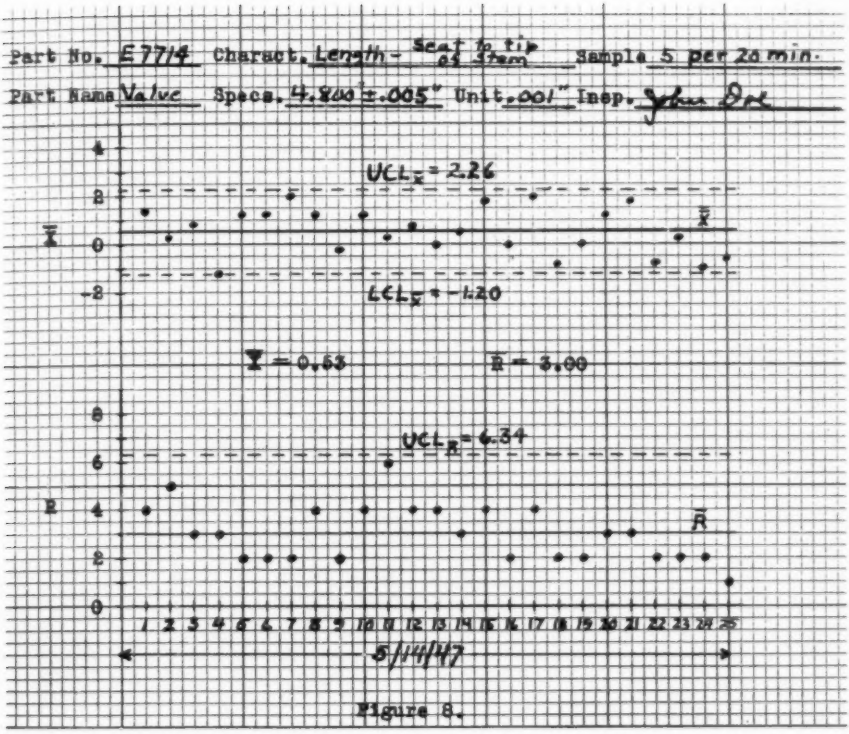

Part No. E7714 Charact. Length - Seat to tip of stem Sample 5 per 20 min.
Part Name Valve Specs. 4.800 ± .005" Unit .001" Inesp. John Doe
UCL$_{\bar{x}}$ = 2.26
LCL$_{\bar{x}}$ = -4.20
$\bar{\bar{x}}$ = 0.63
$\bar{R}$ = 3.00
UCL$_R$ = 6.34
$\bar{x}$
R
$\bar{R}$
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
5/14/47

Figure 8.

Maintaining control. Figure 8 is the climax to this story. Between the time covered by Figure 6 and that covered by Figure 8, mechanical defects were found and corrected in the machine, an automatic hydraulic feed was substituted for hand feed, and the operator learned how to make and hold a setting very near the blue-print mean. The process is in control over this run of 25 samples on both average and range.

Is the control satisfactory? Should we strive for further improvement, or can we predict that if the controls exhibited here are maintained, the process will make acceptable product? To answer these questions, do not compare the control limits on the average chart with the specifications of ±5! What we have to know now is not the spread within which averages can be expected to vary, but rather the spread within which individual pieces can be expected to vary. We can make a satisfactory estimate of this spread only after a process has demonstrated its ability to stay in control over an adequate number of samples (25 or more samples of 5 is considered an adequate number). The valve-length process has now met this criterion.

To make the estimate we want, we use another number calculated by mathematicians. This number is denoted by d_2, and its value also depends on the sample size. It is tabulated in each of Refs. 1 - 3.

For a sample size $n = 4$, we find $d_2 = 2.059$, and for $n = 5$, $d_2 = 2.326$. The ratio of $\bar{R}$ to d_2 gives a number called "sigma-prime of individuals", which is symbolized by σ'_x, where σ is the lower case Greek letter sigma. The total variation, or spread, in the lengths of individual pieces is then approximately $6\sigma'_x$. Moreover, $\bar{\bar{X}} + 3\sigma'_x$ and $\bar{\bar{X}} - 3\sigma'_x$ give boundaries within which practically all individual lengths will vary if the process stays in control at the given $\bar{\bar{X}}$ and $\bar{R}$ values.

For the valve-length process, $n = 5$, so $d_2 = 2.326$, and for the last 25 samples (Figure 8), $\bar{R} = 3.00$ and $\bar{\bar{X}} = 0.53$. Using T_U for the upper specification limit and T_L for the lower specification limit, we have $T_U = 5$. The calculations and comparisons for checking the capabilities of this process against specifications are shown in Table 2.

Table 2 - CHECKING THE PROCESS AGAINST SPECIFICATIONS

$$n = 5 \; ; \quad d_2 = 2.326 \; ; \quad \bar{R} = 3.00 \; ; \quad \bar{\bar{X}} = 0.53$$

$$\sigma'_x = \frac{\bar{R}}{d_2} = \frac{3.00}{2.326} = 1.29$$

$$6\sigma'_x = 7.74 \; ; \quad T_U - T_L = 10$$

$$\bar{\bar{X}} + 3\sigma'_x = 0.53 + 3.87 = 4.40 \; ; \quad T_U = 5.00$$

$$\bar{\bar{X}} - 3\sigma'_x = 0.53 - 3.87 = -3.34 \; ; \quad T_L = -5.00$$

It is clear from Table 2 that control is satisfactory. We can safely predict that if this level and spread are maintained, practically all (around 99% or better) individual pieces will come off this machine within design specifications. Consequently, at this stage of the program we shift our emphasis from attaining control of the process to maintaining control of the product by adopting what are called "standard values for maintaining control". This means that we choose a value for center line on the charts and then fill in with the sample points rather than first plotting the points and then calculating the center lines. A standard value for center line on the average chart is denoted by $\bar{X}'$; that for the range chart by $\bar{R}'$ (or sometimes R'_n). It would be natural to choose $\bar{X}' = 0.50$ and $\bar{R}' = 3.00$ for the valve-length process. We then get a blank chart such as Figure 9.

As future production takes places, the $\bar{X}$ and R values from each periodic inspection are plotted at once on this chart. This is a "road map", if you please, of the highway down which this process has said it can travel as long as it is kept healthy, i.e. as long as no assignable causes enter to disrupt it. We watch the charts for any evidence of impending trouble, such as a shift in level, trends up or down, or an increase (or decrease) in variability. Moreover, a point falling outside a control limit now calls for prompt and vigorous

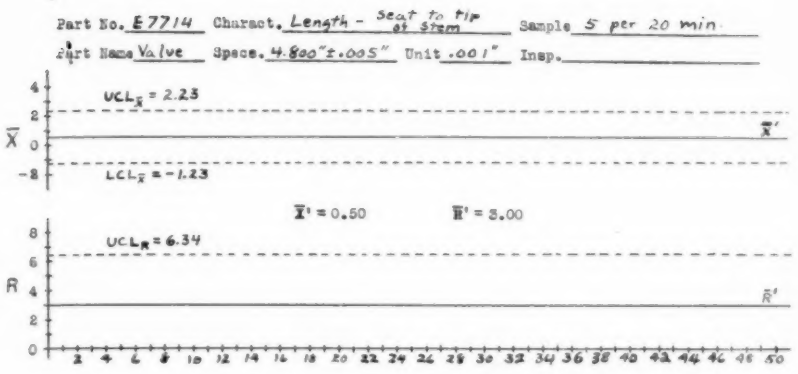


Figure 9.

investigation and corrective action, because it almost certainly did not get out there by chance!

There is also a strong possibility that as time and experience accumulate, there will be further improvement in process variability which will show up as a succession of points all on the low side of the $\bar{R}'$ line. It will then be wise to revise the adopted standards so as to make them consistent with the new process capabilities.

Bench inspection of a sorting type can be entirely eliminated so long as we succeed in maintaining the control mapped out in Figure 9. If something really goes sour in the process, such as a new, inexperienced operator, a breakdown in the machine, or a batch of faulty material, we will catch it at once by the presence of points outside of the control limits. Screening inspection may be necessary for that part of production covered by these samples, and until control is restored.

The control charts thus become powerful instruments for keeping real, finger-tip control of the process. We will know what is happening while it is happening, not two days later after the damage is done! With control chart operation we can build quality into these valves at the machine rather than futilely trying to inspect it in at the inspection crib.

The normal curve and standard deviation. We can touch on this topic only briefly. Ref. 1, pp.47 - 147, gives an excellent, readable, and fuller treatment than we can give it here.

Consider the 125 individual valve-lengths that gave rise to the control chart in Figure 8. If we make a tally sheet of the distribution of these measurements (they are not shown in this paper), it turns out to look like Figure 10. It is easy to see that this arrangement of tally marks forms a pattern of variation that can be outlined approximately by a smooth curve as shown in Figure 11. Such a curve is

called a "frequency curve" because it outlines the distribution of frequencies with which the various measurements in question can be expected to occur.

Tally Sheet

X	Tallies	Freq.
5	I	1
4	II	2
3	𝍸 III	8
2	𝍸 𝍸 𝍸 𝍸 I	21
1	𝍸 𝍸 𝍸 𝍸 𝍸 𝍸 II	32
0	𝍸 𝍸 𝍸 𝍸 𝍸 IIII	29
-1	𝍸 𝍸 𝍸 𝍸 II	22
-2	𝍸 II	7
-3	III	3
		125

Figure 10.

Curve Outline of Tallies

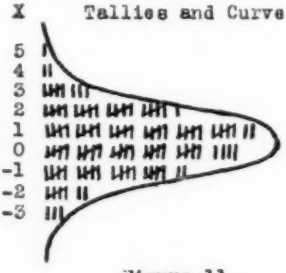


Figure 11.

For an industrial process that is operating in control with respect to averages and ranges, there is a frequency curve known as the "normal curve" which can generally be assumed to represent the variation pattern for the process. This assumption can (and should) be checked by methods explained in the reference already cited. I have heard it said that the normal curve is "the Lord's Prayer in statistics". At any rate, it is a mathematical model for the variation pattern which we find it useful to suppose a controlled process is trying to imitate. The properties of this curve that support control chart operation so effectively are approximated with sufficient accuracy by most controlled processes so that for practical purposes we can attribute these properties to the process.

Figure 12 shows a normal curve and the properties of this curve that are of chief interest in control work. This curve says that ideally more measurements would be concentrated at the average value ($\bar{X}'$) than at any other point along the X scale, and that the further we get away from this average value in either direction, the fewer pieces we can expect to find having these wider measurements. The curve further says that, ideally, the dispersion or spread in the variation of measurements (X values) will be symmetric about the average value, $\bar{X}'$.

But how much total spread will there be? This depends on the calculation for each process of a statistical yardstick called "standard deviation", designated by the symbol σ'_x that we met in Table 2. If σ'_x is small, the total spread for the process will be small; if σ'_x is large, the process will have a wide spread. But small or large, the pattern of variation over this total spread can be expected to resemble the curve shown in Figure 12 if the process is operating in control.

The yardstick, σ'_x, divides the total area under the curve into six panels which have been called, quite appropriately, "chance zones".

Normal Distribution Curve

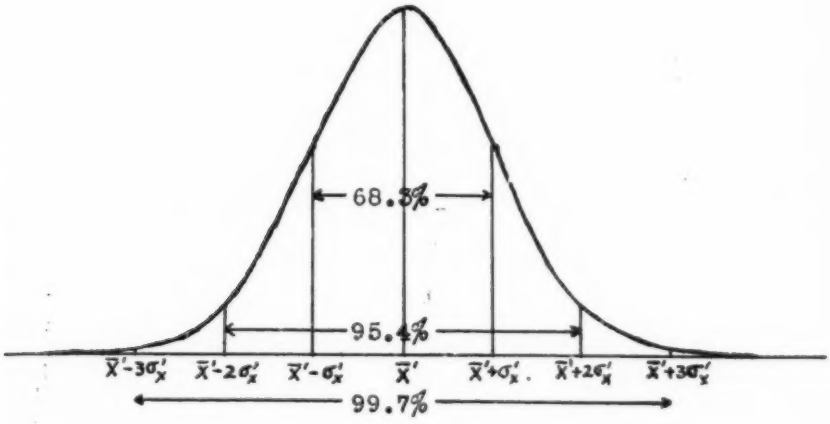


Figure 12.

If the total area under the curve is taken as 100%, Figure 12 shows that, as long as the process continues to operate in control at the level $\bar{X}'$ with a standard deviation of $\sigma'_{\bar{X}}$ we can expect about 68% of production to be within the limits $\bar{X}' \pm \sigma'_{\bar{X}}$, about 95% to be within $\bar{X}' \pm 2\,\sigma'_{\bar{X}}$, and all, or very nearly all (ideally 99.7%), to be within $\bar{X}' \pm 3\,\sigma'_{\bar{X}}$.

It should now be apparent why we compared $\bar{\bar{X}} + 3\,\sigma'_{\bar{X}}$ with T_U and $\bar{\bar{X}} - 3\,\sigma'_{\bar{X}}$ with T_L in Table 2. We were assuming that because the process was operating in control, the individual valve-length measurements would be approximately normally distributed with $\bar{X}' = \bar{\bar{X}} = 0.53$, and with $\sigma'_{\bar{X}} = 1.29$. Hence, we could predict that all, or very nearly all, these lengths would vary between the 3-sigma prime limits of $\bar{\bar{X}} - 3\,\sigma'_{\bar{X}} = 3.34$ and $\bar{\bar{X}} + 3\,\sigma'_{\bar{X}} = 4.40$ as long as this control was maintained. Since these 3-sigma prime limits were within the specifications of ± 5, we could conclude that the process could be counted on to make all pieces within tolerance.

But what does all this have to do with a control chart for averages? Common sense tells us that if individual measurements vary (and they do!), then averages of these measurements must vary also. Which would you expect to have the smaller total spread in variation, averages or individuals? The answer is obviously "Averages." Now it is a fact that if individual measurements follow a normal curve variation pattern, then the averages of samples of these measurements will also follow a normal curve. As a matter of fact, in the long run, averages tend to

follow a normal curve whether or not the individual measurements do. Both the curve for individuals and that for averages must be centered at the same point, $\bar{\bar{X}}$ (or $\bar{\bar{X}}'$), because you will recall that $\bar{\bar{X}}$ was not only the grand average of the $\bar{X}$'s, but also the grand average of all the individual X's.

What about the standard deviation for the curve of averages? It will have to be smaller than the standard deviation for the curve of individuals, because averages must have a smaller total spread than do individuals. How much smaller? The mathematicians tell us that if σ'_X is the standard deviation for individuals, and $\sigma'_{\bar{X}}$ is the standard deviation for averages of samples of n individual measurements, then $\sigma'_{\bar{X}} = \sigma'_X / \sqrt{n}$. Thus, if we use a sample size of $n = 4$, and if the process shows control on both the average and range chart, then we can assert that the standard deviation (and hence, the total spread) for the distribution of averages will be just half as great as that for individuals. The convenient fact that $\sqrt{4} = 2$ is one reason why some quality control men prefer a sample size of $n = 4$ rather $n = 5$.

The control limits on the average chart are placed at a distance $3\sigma'_X$ from the center line. In fact, Shewhart Control Charts in general are designed to place the control limits at 3 standard deviations from the center line of the chart. That is why control limits are often referred to as "3-sigma" limits. For example, the mathematical model for the distribution of ranges in samples drawn from a controlled process is not a normal curve. Nevertheless, the upper control limit on a range chart is placed at a distance of 3 standard deviations in range ($3\sigma'_R$) from the center line, $\bar{R}$, and at this distance it provides a total spread for variation in range which will include all, or nearly all, of the variation to be expected in ranges as long as only natural, random causes of variation are at work in the process. Thus, the 3-sigma control limit provides a practical criterion for distinguishing random from assignable sources of variation in range, which is what a 3-sigma control limit is for on any control chart.

Let us check the contention that $UCL_{\bar{X}} = \bar{\bar{X}} + 3\sigma'_{\bar{X}}$ and $LCL_{\bar{X}} = \bar{\bar{X}} - 3\sigma'_{\bar{X}}$. For the details, see Figure 13.

Figure 14 shows in outline the variation pattern for individuals and averages which we can assume represents the process that gave rise to the control chart for averages shown in Figure 8. Figure 15 shows this same variation pattern transferred to the control chart blank for maintaining control that we set up in Figure 9. The curves are drawn with broken lines because they are not part of the chart. Nevertheless, this is the picture you should always see in your mind's eye when you look at a chart for a controlled process. It is a sort of silhouette of the "universe", or process variation pattern, from which the points, as they are plotted on the chart, are coming as long as the process remains in the control predicted by the chart.

Figure 13.

CONTROL LIMITS ARE 3-SIGMA LIMITS

We found: $UCL_{\bar{\bar{X}}} = \bar{\bar{X}} + (A_2)\bar{R} = 2.23$

$LCL_{\bar{\bar{X}}} = \bar{\bar{X}} - (A_2)\bar{R} = -1.20$

$\sigma_X' = \bar{R}/d_2 = 1.29$; $\bar{\bar{X}} = 0.53$.

We want to show that: $\bar{\bar{X}} + 3\sigma_{\bar{X}}' = 2.23$

$\bar{\bar{X}} - 3\sigma_{\bar{X}}' = -1.20$.

Now $\sigma_{\bar{X}}' = \sigma_X'/\sqrt{n}$, so with $\sigma_X' = 1.29$ and $n = 5$,

we have: $\sigma_{\bar{X}}' = 1.29/\sqrt{5} = 1.29/2.236 = 0.577$.

Hence, $3\sigma_{\bar{X}}' = 3(0.577) = 1.73$.

Therefore, $\bar{\bar{X}} + 3\sigma_{\bar{X}}' = 0.53 + 1.73 = 2.23 = UCL_{\bar{\bar{X}}}$

$\bar{\bar{X}} - 3\sigma_{\bar{X}}' = 0.53 - 1.73 = -1.20 = LCL_{\bar{\bar{X}}}$

(It is just a coincidence that $\sigma_{\bar{X}}' = A_2 = 0.577$ for these data. This would not be true in general, but the argument used here would lead to verification in every case.)

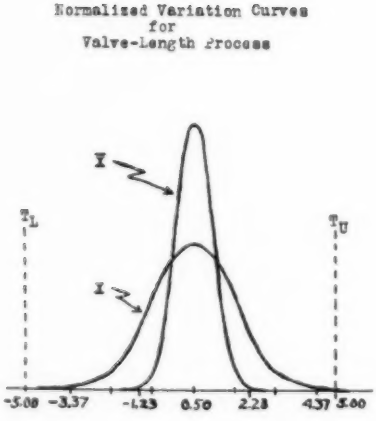


Figure 14.

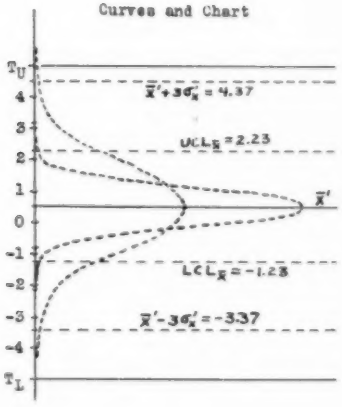


Figure 15.

Conclusion. We have only hit the high spots in this discussion. If your imagination has been stimulated and your appetite for further reading has been whetted, our time together here will have been well spent. We have tried to describe how to get and record measurement chart data, how to construct an $\bar{X}$ and R chart, how to interpret the charts, how to distinguish process from product control, how and when to use measurement charts for maintaining control at the optimum capabilities of the process relative to specifications, and something of how to tie in the operational procedures for measurement charts with the mathematical theory that supports these procedures.

It seems reasonable to assert that any man with average intelligence, imagination and practical knowledge of a manufacturing process should be able to grasp the few fundamental and essentially simple ideas required to make a start with control chart operation, and to appreciate the power and potential usefulness such operation can yield toward the improvement of product quality and the reduction of production costs.

References

1. E. L. Grant, Statistical Quality Control, McGraw-Hill, N.Y.C.

2. Paul Peach, Industrial Statistics and Quality Control, Edwards and Broughton, Raleigh, N. C.

3. American Standards Association, Control Chart Method of Controlling Quality During Production, ASA American War Standard Manual Z1.3 - 1942, 70 E. 45th Str., New York 17, N.Y.

ATTRIBUTE CHARTS IN QUALITY CONTROL

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Introduction. During this session we shall consider in some detail the background, construction, and interpretation of that class of Shewhart Control Charts known as "attribute" charts. These charts must be used to study certain types of quality characteristics, and they may be used very generally for almost any quality characteristic. The situation that makes their use appropriate is easy to recognize, and may be characterized as follows. Any inspection procedure that merely counts the number of appearances of a given quality characteristic without undertaking to measure the characteristic directly is an attribute test, and data gathered by such inspections lead to attribute charts.

Examples are legion. All tests conducted by use of go, no-go gauging equipment are attribute tests, because they do not measure the degree of conformance, they yield only a "Yes" or "No" answer. For instance, in a drop-test for paper bags, a given bag either breaks or does not break when subjected to the test; there would be little useful information furnished by trying to measure how much of a break occurred. Likewise, all visual inspection tests are attribute tests. Thus, surface defects are either seen and counted, or not seen and passed -- there is generally no attempt to measure the magnitude of each defect. The percent of scrap in a day's production, the number of order-filling errors per 100 orders serviced, the number of mis-soldered connections per set in a radio assembly, the number of mis-picks or dropped threads per bolt of cloth, the number of breaks or weak spots in insulation per 1000 yards of insulated wire, the ratio of total rejections to total units inspected at final inspection per week, and so on, are further examples. You can (and should) think of additional examples from inspection procedures at your own plant that are attribute tests.

On the other hand, consider an electric fuse whose response time is to be checked. The inspection test could be either attribute or measurement. Thus, we might take each fuse in a sample from a given lot, subject it to a specified circuit test, and count the number that failed to blow within a given tolerance time under this test. If this number were too high, the lot sampled would be under suspicion, and might be rejected. This would be testing on an attribute basis. Suppose, however, that we measure the time of blow under the specified circuit test for each sample fuse. This would be testing on a variables basis, and measurement ($\bar{X}$ and R) charts rather than attribute charts would be the appropriate type for charting such data.

Thus, there are quality situations where either attribute or measurement charts could be used, depending on the kind of information wanted and the nature of the inspection test. In general, attribute charts are simpler and less expensive to maintain than are measurement charts. They are also more flexible in that several different quality characteristics can be covered by a single chart, whereas each separate characteristic requires its own $\bar{X}$ and R chart. However, in

exchange for these advantages, one loses some degree of sensitivity when an attribute chart is used in place of a measurement chart, because, quite clearly, an attribute chart cannot provide the detailed information about a quality characteristic that is available in an $\bar{X}$ and R chart. For example, we know more about the characteristic "time-of-blow" for fuses when we measure it than we do when we set a fixed time limit and merely count the number of fuses that conform or fail to conform to this time tolerance.

With these rather general notions as an introduction to the surname "attribute" charts, let us consider them in order by their Christian names. The three best known members of this family (and the only ones we shall consider) are: (1) "fraction defective", or "p" charts, (2) "number defective", or "np" charts, and (3) "number of defects per unit", or "c" charts.

The Fraction Defective, or p Chart

Getting the data. Consider an enamelling process where the product is given a 100% visual inspection before going to assembly. Suppose there are six major defects, the occurrence of any one of which on the piece inspected will render it classifiable as a defective and prevent its going on to assembly. Suppose that about 1500 - 1600 pieces pass through the inspection station every eight hour day. How shall we record inspection data for this product and use these data to keep a control chart that will show the variation in, and general level of, the proportion of production rejected at this station?

Figure 1 shows a record form that would be useful for the purposes mentioned. In practice, the defect columns headed A through F would show the actual defect by name, rather than by letter designation. Record forms for p chart data are easy to devise. The particular headings and column arrangement, and the amount and nature of accessory information to be accommodated, can be readily adjusted to suit the special needs of the problem under study. The essentials that every such form must have are: (1) sample identification by number and time, (2) number of units inspected in each sample, (3) number of units in each sample found to be defective for any or all reasons, and (4) the ratio, for each sample, of item (3) to item (2). The form shown in Figure 1 provides these essentials, and, since rejection of a given piece can be made for more than one defect, provision is made also for checking the reasons for rejection. Thus it will be easier to track down sources of trouble responsible for poor quality. We need a minimum of 10 samples to make a chart; our record sheet gives data for 20 samples.

Note that each sample size here is 200. Since this is a 100% inspection situation, the results have to be subgrouped in some manner for control chart purposes. With daily production about 1500 - 1600, a sample size of 200 will furnish about one point an hour on the chart. After each 200-th inspection, the inspector merely begins entering rejections on the next sample line.

The question of sample size for p chart work is of key importance. In the first place, it is not always possible to maintain a constant

Figure 1 - Control Chart Data Sheet

Part Name Side Panels Part No. K-30-L-R

Operation Enamelling Assembly No. K-30

Insp. Stat. 4 Inspector John Q. Doe

Sample No.	Date & Hour	Number Insptd. n	Number Defect. np	Fraction Defective p (%)	Defects A	B	C	D	E	F	Notes
1	4/4/47 10 AM	200	12	6.0	3	2	0	4	2	1	
2	11	"	21	10.5	6	3	3	4	3	2	
3	2:30	"	9	4.5	5	0	1	2	0	1	
4	3:30	"	32	16.0	10	4	3	14	1	0	
5	4:30	"	24	12.0	8	3	0	11	6	2	
6	4/7/47 9 AM	"	10	5.0	4	3	0	3	0	0	
7	10	"	17	8.5	3	3	3	3	4	1	
8	11	"	7	3.5	2	0	1	1	1	2	
9	12	"	20	10.0	5	2	4	4	3	2	
10	1:30	"	0	0.0	-	-	-	-	-	-	
11	2:30	"	8	4.0	2	1	2	1	1	1	
12	3:30	"	3	1.5	0	0	3	0	0	0	
13	4:30	"	24	12.0	9	2	3	8	2	0	
14	4/8/47 9 AM	"	20	10.0	6	1	2	4	3	4	
15	10	"	19	9.5	3	3	4	3	3	3	
16	11	"	31	15.5	10	1	5	12	2	1	
17	12	"	14	7.0	2	4	2	3	1	2	
18	2	"	23	11.5	5	2	4	7	3	2	
19	3	"	16	8.0	8	0	0	8	0	0	
20	4	"	18	9.0	8	1	0	7	1	1	
Totals		4000	328		99	35	40	99	30	25	

sample size. Thus, if we were to take daily production as sample size in our example, we would have samples of varying size from day to day, and only one point per day on the chart.

In the second place, when a choice is possible, sample size should be chosen in some relation to the expected average quality level. Thus, if the quality level is as good as ½% defective on the average, we would need a sample size of at least 200 to give any defectives a decent chance to show up in the samples. On the other hand, if the quality level were as bad as 15% defective, we could get useful data with as small a sample size as 10. For a p chart to be an effective control tool, we need samples that can be expected to contain some defectives. It is the old story of not being able to get something from nothing: if sample size is too small relative to quality, not enough defectives are picked up to give a good reflection of process variability with respect to the attribute being tested. If sample size is too large, relative to the quality level, we should probably be doing more inspection than is necessary for the maintenance of an adequate p chart. There are no sharp criteria for deciding when a sample size is "large" or "small", or when quality is "high" or "poor", but the general principle is: relatively large subgroup size for sampling product of high quality, relatively small subgroups for sampling product of poor quality.

There is a good discussion of this whole question of sample size for attribute charts, as well as a readable and thorough presentation of the entire topic of p charts, in Chapt.X of Ref.1. Ref.2 also contains much helpful guidance in connection with these charts.

Making the chart. Turning our attention now to the construction of the chart, let us note first that the variable which is plotted on a fraction defective chart is the ratio p, defined, as one would expect, by

$$p = \frac{\text{no. of defective units found in the subgroup inspected}}{\text{total no. of units in the subgroup inspected}}$$

This definition implies that the chart will require a horizontal sample identification scale (numbered from zero through 20 for our data) and a vertical axis scaled as a pure number in some suitable unit to accommodate the p values to be plotted. Values of p may, of course, be plotted either as decimal numbers between zero and one, or as percentages. The latter plan is favored in most shop applications, and is the one we shall follow. For our data, the p axis is scaled from zero through 18.

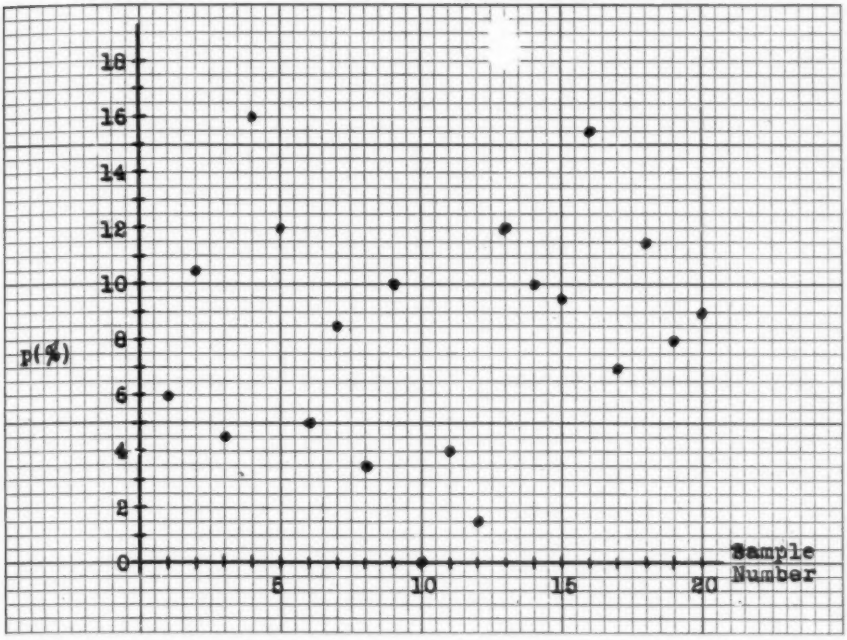
Figure 2 shows this much of the job completed. It is not yet a control chart, because it lacks a center line and control limits. These we now proceed to supply.

The center line, or average fraction defective, designated by $\bar{p}$, is defined as follows:

$$\bar{p} = \frac{\text{total no. of defectives found in ALL subgroups inspected}}{\text{total number of units in ALL subgroups inspected}}$$

This definition will yield the correct value of $\bar{p}$ regardless of whether sample size varies or remains constant. For our data, we have, from Figure 1, $\bar{p} = (328)/(4000) = 0.082 = 8.2\%$. We plot this as a solid line on the chart.

Figure 2 - Enamelling Operation Data (p) Plotted



It is clear from Figure 2, and from what has just been said, that the fraction defective, p, in these 20 samples varied, and that it varied about an average level of $\bar{p}$ = 8.2%. It must therefore follow that there should be some way to describe this variation numerically, and in particular, there should be some criterion or yardstick for deciding whether or not the variation in p is consistent with its expected (average) value, $\bar{p}$. Mathematical theory (which, curiously enough, originated with the study of certain gambling problems over 200 years ago!) supplies the yardstick we need here, and, as you may have guessed, it is the standard deviation of p, denoted by σ_p. The control limits on a p chart are then placed at 3 σ_p from the center line $\bar{p}$. Points on a p chart may vary within these limits by chance only, but points outside these limits are not consistent with the average, $\bar{p}$. Their presence outside the limits justifies the contention that they got out there as a result of some assignable cause (or causes) not natural to a process operating at a level of $\bar{p}$.

But how do we calculate σ_p ? For a series of p values all based on the same sample size, n , the formula is

$$\sigma_p = \sqrt{\bar{p}(1 - \bar{p})/n} \ .$$

Consequently, using UCL_p for "upper control limit on p", and LCL_p for "lower control limit on p", we have

$$UCL_p = \bar{p} + 3\sqrt{\bar{p}(1 - \bar{p})/n}$$

$$LCL_p = \bar{p} - 3\sqrt{\bar{p}(1 - \bar{p})/n} .$$

(In case you don't like to use a slide rule or extract square root, a very simple and quite complete table for getting these limits without root extraction appeared in the Nov. 1944 issue of Industrial Quality Control in an article by H. Reinhardt and E.D. Benson of the Sylvania Electric Products, Inc., Ipswich, Mass.) Sometimes the LCL_p turns out to be a negative number, in which case it is assigned the value zero, and is not put on the chart.

Figure 3 - Analysis of Data for p Chart

$$\bar{p} = \frac{\text{total no. defective}}{\text{total no. inspected}} = \frac{328}{4000} = 0.082 = \boxed{8.2\%}$$

$$\sqrt{\frac{\bar{p}(1 - \bar{p})}{n}} = \sqrt{\frac{(0.082)(0.918)}{200}} = \sqrt{0.00037638} = 0.0194$$

$$UCL_p = \bar{p} + 3\sqrt{\bar{p}(1 - \bar{p})/n} = 0.082 + 3(0.0194)$$

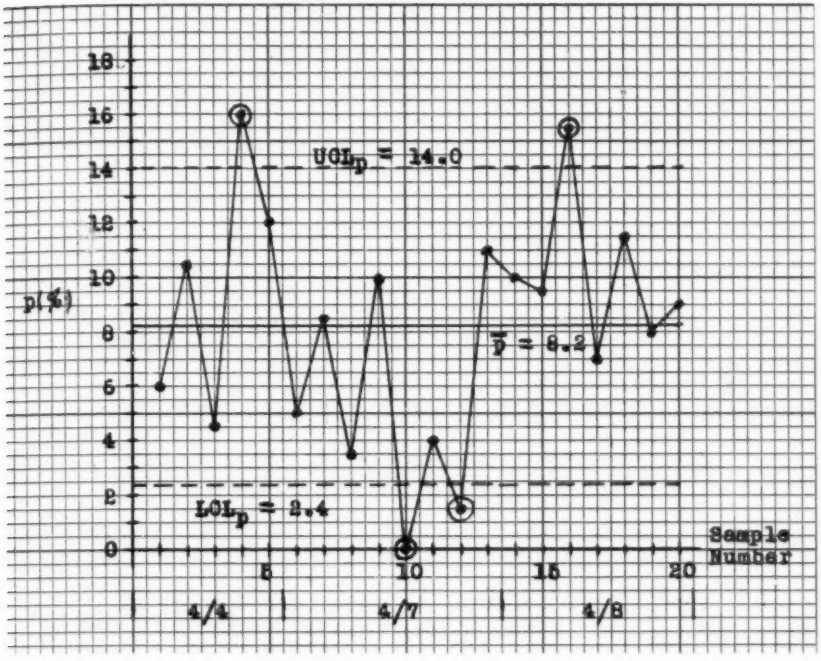
$$UCL_p = 0.082 + 0.058 = 0.140 = \boxed{14.0\%}$$

$$LCL_p = \bar{p} - 3\sqrt{\bar{p}(1 - \bar{p})/n} = 0.082 - 0.058 = 0.024 = \boxed{2.4\%}$$

For our data we find $UCL_p = 14.0\%$ and $LCL_p = 2.4\%$. These are plotted as broken lines on the chart. Figure 3 summarizes the formulas and calculations we have been discussing, and Figure 4 shows the completed chart for the data of Figure 1. The points on this chart have been connected by straight line segments. The only real reason for taking the time to draw in these lines is that the resulting chart has more eye appeal and is, therefore, somewhat easier to follow. We shall consider this a sufficient reason for connecting the points on all subsequent attribute charts used in this paper.

Interpreting the chart. The chart in Figure 4 shows the process operating at a level of $\bar{p} = 8.2\%$, and out of control at this level. Sample #4 and sample #16 show too high a percent defective, and samples 10 and 12 show too low a percent defective to be accounted for as chance variations for a process supposed to average 8.2% defective. Looking at the defect record, we note that defects A and D predominate, not only at samples 4 and 16, but as totals for all 20 samples. Investigation and corrective action to improve these two components of quality should help to establish control, and to do so at a level lower than 8.2%. It might even be a good idea to keep a separate chart for a time on each of the sources in the process contributing to defects of type A and D. Note also that samples 4 and 16 were taken at about the same time of day. This fact should be kept in mind in making an investigation. Frequently the only clue given by

Figure 4 - Enamelling Operation p Chart



a p chart as to the cause of trouble is the record of when the trouble occurred.

Points below the lower control limit on a p chart deserve just as careful study as do those that are out on the high side. Such points, when investigated, may lead to the discovery of some source of improvement that can be permanently worked into the process. They may also be an indication of faulty inspection procedures, or relaxation of inspection standards, which need to be corrected. It may take some persuasion to convince operating personnel that a process is "out of control" when a sample point shows quality apparently so much better than average that it plots below the lower control limit! Nevertheless, it is always wise to investigate such points for the reasons mentioned.

There is, of course, no range chart associated with attribute charts. On these charts, process variability, or spread, depends upon process average, e.g., on a p chart σ_p is defined in terms of $\bar{p}$. It follows that, for a fixed sample size, n, the lower the process average, $\bar{p}$, the less spread or variability there will be in fraction defective from sample to sample in a controlled process. There are thus two "controls" on an attribute chart: (1) the level ($\bar{p}$ for a p chart), which we want to be as low as is economically feasible, and (2) the spread ($UCL_p - LCL_p$, or $\bar{p} \pm 3\sigma_p$, on a p chart), within which we want all, or nearly all, process variability to fall if we

are to have a process that is operating in control, i.e., in a predictable, consistent manner. For the enamelling process, it seems unlikely that a level of 8.2% defective is as good as would be economically feasible, and even if it were, we would want the process to operate more consistently with respect to this level than it did over the 20 samples charted in Figure 4. Thus, there is a clear challenge in this chart to go to work on the process and improve its performance.

Adoption and use of standard values. How about control versus satisfactory control with an attribute chart, in particular, a p chart? A process is operating in satisfactory control with respect to fraction defective when (1) the level, $\bar{p}$, is as low as is economically feasible, and (2) the process operates in control at this level. Since there are generally no objective criteria (such as blue-print specifications) for attribute charts, the level to be considered satisfactory must be set in terms of the best performance the process is capable of delivering for the money we can afford to spend on it. Maybe we could get the process to operate at a level very near zero if we spent enough time and money on it. But unless the expense of such refinement were justifiable, it would be better business judgment to accept control at some higher level.

Suppose it is decided for our enamelling example that 3% defective would be a level at which the process could be operated very profitably if we could get and hold it down to this level without too much expense. If it turns out that the process can do better than this, then that will be just so much velvet, but we are willing to settle for 3%. Control limits, for a sample size of 200, will then be $UCL_p = 6.6\%$ and $LCL_p = 0$. How shall we arrive at this happy state?

There is an old saying that if you have to eat an elephant, the best way to go at it is one bite at a time! Our plan (and that which has been successful in many applications) will be to adopt a trial standard for the next 20 samples, set up a blank chart based on this standard, and see what happens as we go to work to improve the process. But we will not try to get all the way down from 8.2% to 3% in one jump! If we assume that samples 4 and 16 are due to assignable causes which we can locate and remove, we can argue that the $\bar{p}$ for the other 18 samples will be $(265)/(3600) = 0.0736 = 6.36\%$. But the assignable causes responsible for samples 4 and 16 must also have some effect on the other samples, so 7.36% is still higher than we can expect after corrective action has been taken on these causes. Let's be conservative, and aim for 6%. The symbol p' is used for a standard value, $\bar{p}$ being reserved for an actual computed value based on process data. With sample size $n = 200$, we then have $p' = 6\%$, $UCL_p = 11.0\%$, and $LCL_p = 1.0\%$.

These lines (or at least the center line $p' = 6\%$) are then posted on the chart, which we keep where operating personnel can see it, and we watch the returns come in, posting on the chart each sample point as its value is determined by the inspection results. If you want to see some fun, try this out in your plant on some process where you

feel sure improvement can be made, and where the operating personnel are willing to go along with you on the use of this new "gadget". A p chart makes sense to most shop people -- they are used to thinking in terms of percentages. If you feel the control limits are going to present a hazard, keep them to yourself in your little black book for a discreet period of time, and leave them off the chart in the shop. Human nature being what it is, if you choose a standard, p', that can be met or bettered, you will be in a position to capitalize on a powerful natural instinct: the competitive spirit. If you deserve and have the confidence of operating personnel, set up a reasonable standard, p', as a bogey, and watch them whittle it down for you! There are many actual cases on record where the mere presence of a p chart in an operating area has brought quality improvement without any other action having been taken!

Figure 5 - Enamelling Operation p Chart Continued

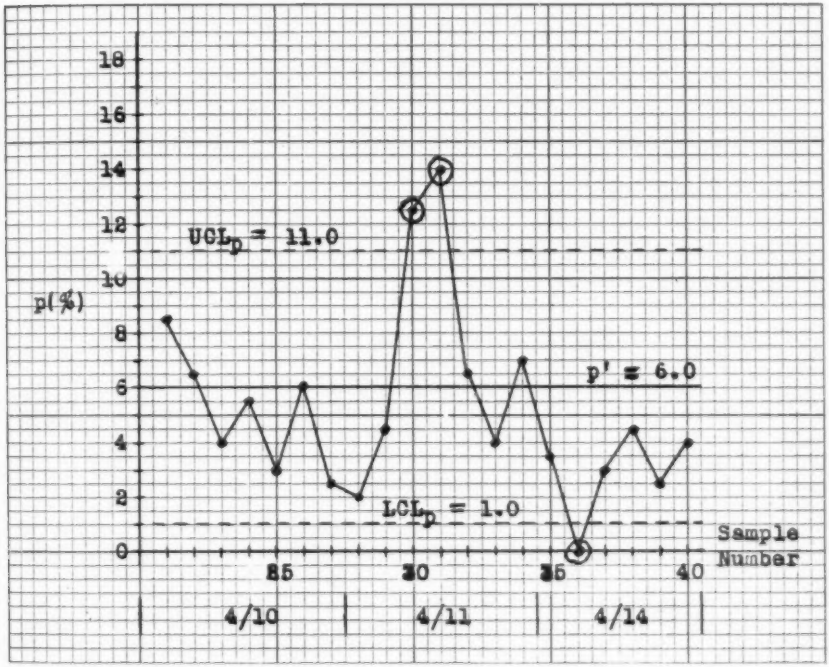


Figure 5 shows what happened in our enamelling process. We were too conservative. Corrective action on the process and the cooperation of operating personnel actually brought the level down to 5.2%, although we have not yet succeeded in establishing control. But a 37% reduction in process level in one jump is a real improvement. It turns out that defect type C was responsible for both of the high points at samples 30 and 31; no explanation was found for the low point at sample 36. Now shoot for p' = 4.5% , which will give control limits at UCL_p = 8.9% and LCL_p = 0.1% .

Figure 6 - Enamelling Operation p Chart Continued

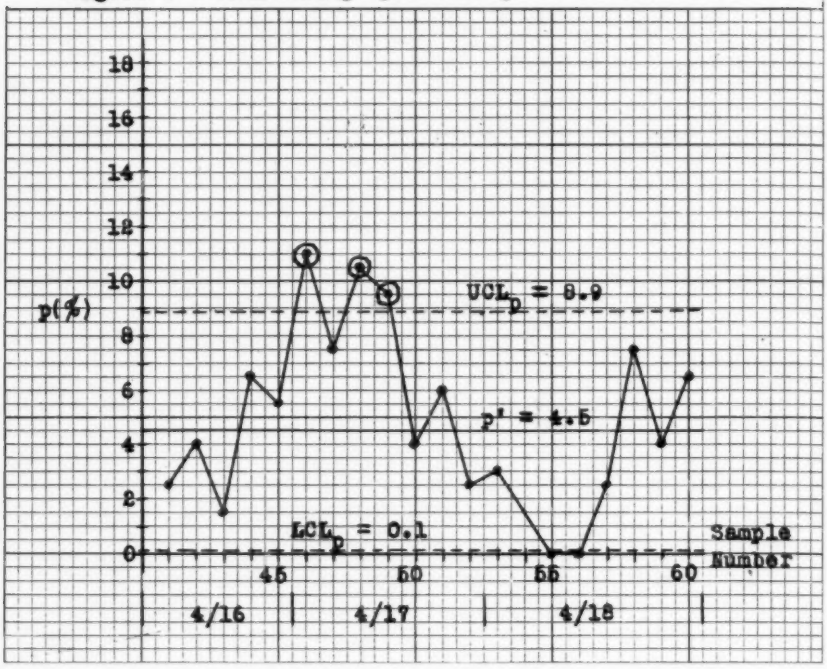
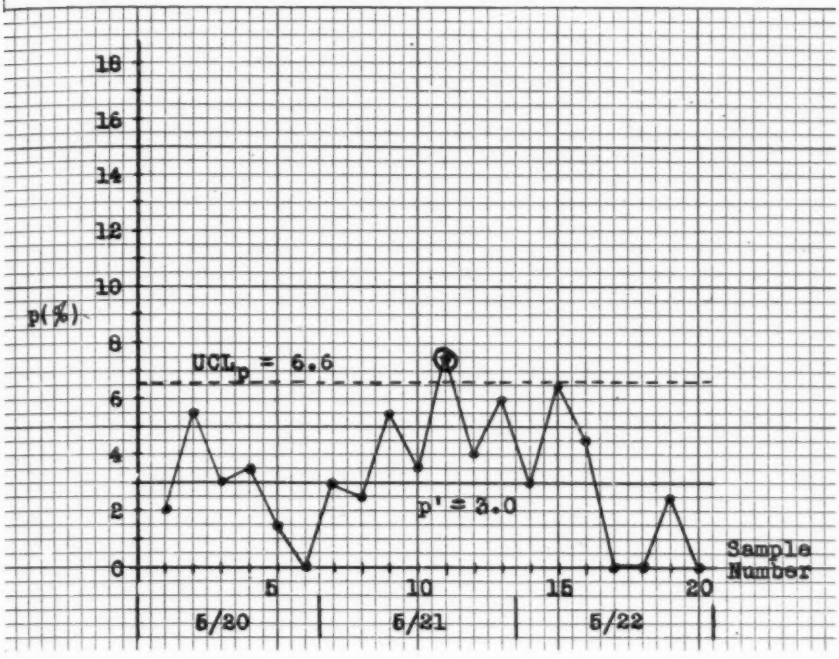


Figure 6 shows what happened during the next run of 20 samples. We did not quite make the $p' = 4.5\%$ goal, the process value here being $\bar{p} = 4.8\%$. Samples 46, 48, and 49 show that there are still some "bugs" in the process. But there are two zero points on this run, and with an LCL_p of 0.1%, p = 0 can scarcely be regarded as an out-of-control value. Even so, it would be wise to look into these two zero points. Maybe the law of diminishing returns is beginning to operate here; maybe a goal of $p' = 3\%$ is too expensive to try to reach. On the other hand, this process has been under the stimulus of control chart operation for less than two weeks. In that time we have skimmed the cream off the job, we have pretty well licked all the easy problems! Now is the time to roll up our sleeves and really go to work on this process, bringing to bear on the problem all the imagination, initiative, and good, solid engineering effort consistent with reasonable costs. Maybe we can still squeeze some more improvement into the process!

Figure 7 shows the ultimate triumph. After further work and experience under control chart operation, the sights have been set at $p' = 3\%$, and for these 20 samples the process has actually averaged $\bar{p} = 3.2\%$ with just one point outside the control limit. A fraction defective of 7.5% would have been considered better than average ($\bar{p} = 8.2\%$) to start with, but the laws of probability say very emphatically that a fraction defective of 7.5% from a process supposed to average 3.2% is just as unlikely a variation as 14.9% would be for

Figure 7 - Enamelling Operation p Chart Concluded



a process operating at an average of 8.2% . Variations in p have to be considered against the background of the cause system from which they came, and the laws of probability guarantee that a system for which $\bar{p}$ = 3.2% is a very different system from one for which $\bar{p}$ = 8.2% , sample size being the same in both cases. However, with the process operating as close to the desired level of 3% as this one is, we shall not be too unhappy if occasionally a point goes over the control limit.

Neither shall we accept it complacently! Our job now is to keep the goal set at p' = 3% and keep the process in control at this level. If we keep our guard up, follow through on every evidence of deteriorating quality, such as a run of 7 or more points all on the high side of the center line, or one or more points outside the UCL_p, and continue to make appropriate corrective action as occasion requires, it is not at all unlikely that in time we may succeed in working this process down to a level even closer to zero than 3%. It has happened just this way in many actual applications. But if 3% is an acceptable level, we shall concentrate our efforts on maintaining control at a level no worse than 3%, regarding any further improvement as a dividend on this investment.

Summarizing this section on standard values for attribute charts, we note the following points.

(1) Make a chart based on process values for an adequate number of samples (preferably 20 to 30), getting the data either from past inspection records or current production.

(2) Study the chart and the process, and either make further trial-run charts based on process values, or adopt a trial standard, and see if the process can be made to equal or better this standard. If you set a standard at an early stage in control operation, be sure you set it high enough on the chart so that there is a good chance of beating it on the next run.

(3) Keep working on the process. Remember the chart does not improve quality, it only reflects quality. The chart can help very much, but the actual improvement in quality comes in the process rather than the chart.

(4) Ultimately you will be able to discover the optimum level at which the process can be operated consistent with the quality desired and the money that can be spent to get this kind of quality.

(5) See that the chart is used to maintain control at the optimum level. This means taking corrective action whenever it is called for. It also means reviewing the standard periodically and revising it if necessary to keep the chart consistent with process capabilities should further improvement take place.

Other uses of p charts. Since this is a techniques session, we shall not dwell long on this topic. However, it is not to be inferred that p charts are restricted to process control. They are a versatile form of control chart, and hence they have a wide range of usefulness. In particular, they are valuable adjuncts of acceptance sampling at incoming inspection. They furnish a simple, graphic record of a vendor's quality level on submitted material, and they tell whether or not he is operating in control at this level. They are excellent charts for giving an over all quality picture for a whole department or area of operation in a plant. Because they have the ability to summarize quality history in terms of percentage, p charts are a "natural" for reporting quality results to management. In fact, the p chart has often been called a "management chart".

The Number Defective, or np Chart

Nature and construction of an np chart. Whenever the inspection procedure can be designed so that the subgroup size remains constant from sample to sample, it is only necessary to enter on the data sheet the number defective found in each sample. Thus we are saved the necessity of calculating the ratio p for each sample, and the data sheet of Figure 1 is reduced by eliminating the p column. The corresponding control chart is called a "number defective", or "np" chart. Such a chart is simply a special adaptation of a p chart, possible only when the subgroup size, n, remains constant for each sample inspected. The variable plotted on this chart is the number defective, denoted by np, so the vertical axis is scaled accordingly rather than as a percentage figure.

The center line, or "average number defective" per sample is denoted by $n\bar{p}$. This average value is defined by

$$n\bar{p} = \frac{\text{total no. of defectives found in all subgroups inspected}}{\text{total number of subgroups inspected}}$$

The inspection procedure for the enamelling process was designed to operate with a constant subgroup size of $n = 200$. Hence, we could just as well have kept an np chart as a p chart for the inspection data from this process, plotting the np values from the record sheet in Figure 1 rather than the p values. Had we done so, the center line for the first 20 samples would have been located at the point determined by dividing the total of the np column by 20, i.e., for these data $n\bar{p} = (328)/(20) = 16.4$ defectives per sample. Note, of course, that, since $n = 200$ for these data, we must have $200\bar{p} = 16.4$, or $\bar{p} = 0.082 = 8.2\%$.

Looked at another way, we see that an np chart is simply a p chart (based on constant subgroup size) with every number on the vertical scale multiplied by n. This implies, of course, that every p value is multiplied by n (which is true) to give np, and that the center line, $\bar{p}$, is multiplied by n to give the center line $n\bar{p}$ on the number defective chart.

We can therefore expect that the control limits on the np chart would be obtained by multiplying those on the p chart by n. Now $UCL_p = \bar{p} + 3\sqrt{\bar{p}(1 - \bar{p})/n}$. Hence, $UCL_{np} = n\bar{p} + 3n\sqrt{\bar{p}(1 - \bar{p})/n}$, and this is indeed correct. But if we want to get the limits directly without resort to those on the p chart, we use a little high school algebra on the last formula above and come up with the result

$$UCL_{np} = n\bar{p} + 3\sqrt{n\bar{p}(1 - \bar{p})} .$$

The corresponding lower limit is therefore given by

$$LCL_{np} = n\bar{p} - 3\sqrt{n\bar{p}(1 - \bar{p})} .$$

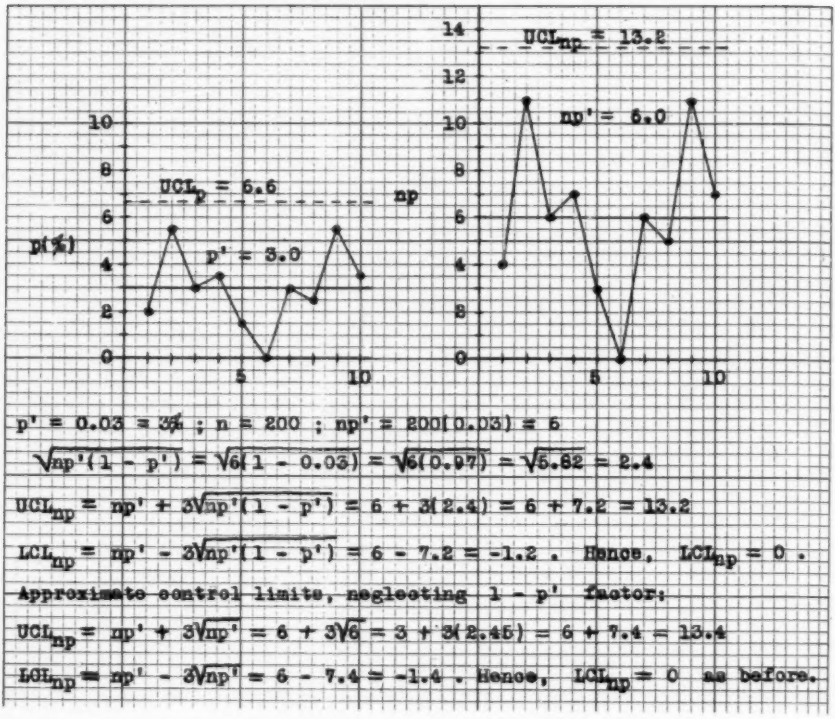
In case LCL_{np} turns out to be negative, we do not plot it on the chart because it is not possible to have fewer than no defectives in a sample.

A further simplification is possible in calculating the control limits on an np chart when it happens that n is greater than 10 and $\bar{p}$ is less than 0.05. Under these circumstances $1 - \bar{p}$ is very nearly one, so the control limits can be approximated with sufficient accuracy for most practical purposes by the formula $n\bar{p} \pm 3\sqrt{n\bar{p}}$.

Finally, all that has been said concerning the adoption of standard values for a p chart, and the use of a p chart based on a standard value, p', applies with equal force to an np chart. The standard value for an n_p chart is denoted by np', and this standard would be chosen and used subject to the same considerations previously discussed.

Figure 8 shows the first 10 samples of the p chart in Figure 7 compared with the corresponding np chart for these same 10 samples.

Figure 8 - Comparison Between p and np Charts



$p' = 0.03 = 3\%$; $n = 200$; $np' = 200(0.03) = 6$

$\sqrt{np'(1 - p')} = \sqrt{6(1 - 0.03)} = \sqrt{6(0.97)} = \sqrt{5.82} = 2.4$

$UCL_{np} = np' + 3\sqrt{np'(1 - p')} = 6 + 3(2.4) = 6 + 7.2 = 13.2$

$LCL_{np} = np' - 3\sqrt{np'(1 - p')} = 6 - 7.2 = -1.2$. Hence, $LCL_{np} = 0$.

Approximate control limits, neglecting $1 - p'$ factor:

$UCL_{np} = np' + 3\sqrt{np'} = 6 + 3\sqrt{6} = 3 + 3(2.45) = 6 + 7.4 = 13.4$

$LCL_{np} = np' - 3\sqrt{np'} = 6 - 7.4 = -1.4$. Hence, $LCL_{np} = 0$ as before.

Shown also are the direct calculations for making an np chart based on a standard value of $np' = 6$ Since $n = 200$ and $p' = 0.03$, the control limits may be approximated, and this calculation is also shown. The fact that np can occur only as a whole number suffices to show that the approximate $UCL_{np} = 13.4$ is just as useful as the exact $UCL_{np} = 13.2$ for the purpose of distinguishing an in-control from an out-of-control point. It is certainly clear from Figure 8 that both charts tell exactly the same story but in a different language, the p chart speaking in the language of percent defective, the np chart in the language of number defective. The point to remember is that whenever the subgroup size can be kept constant, the np chart may be used; whenever the subgroup size varies from sample to sample, the p chart must be used.

The problem of variable sample size. Call the appearance of a "tail" on a penny a "defective". Whether you toss 10, 20, or 50 pennies, the average percent of defectives you can expect to get in a series of tosses will be pretty close to 50%. But the average number of defectives, i.e. "tails", will certainly depend on whether you are tossing 10 pennies, 20 pennies, or some other number of coins. This illustrates the principle that underlies the warning against using an np chart when the subgroup size varies. Every time the sample size changes, the center line on an np chart will shift,

but the center line on the corresponding p chart will not be affected by varying n. We want a change in the center line to reflect a change in process level, not a change in subgroup size. Hence, to make an np chart effective, we must maintain a constant subgroup size. This leaves the p chart as our only alternative in the many situations where we have to accept the possibility of n changing from sample to sample.

Unfortunately, however, even on a p chart, complications arise when n varies. Here the difficulty is with the control limits. These limits involve the formula $3\sigma_p = 3\sqrt{\bar{p}(1-\bar{p})/n}$. It does not take a college education to see that even with $\bar{p}$ remaining constant, the value of this expression will change every time n changes. Furthermore, as n increases, $3\sigma_p$ will decrease, and as n decreases, $3\sigma_p$ will increase. What this boils down to for practical purposes is that as sample size gets larger, the control limits on a p chart come closer together, and as sample size gets smaller, the control limits spread further apart. Thus, to be theoretically correct, a p chart based on variable sample size would have a fixed center line, but the control limits would zig-zag all over the chart, changing direction every time n changed. Such a chart would be anything but popular around the shop! You will find examples of such charts in Ref.1, p.35 and p.257.

A compromise that is generally quite satisfactory consists of basing control limits for the p chart on an average sample size, $\bar{n}$. This gives control limits parallel to the center line over most of the chart. It may be necessary to make an adjustment, i.e., a break, in these level control limits when either (1) a particular sample point is based on a sample size, n, that is too far away from the average value, $\bar{n}$, or (2) a particular sample point plots very close to the limits based on $\bar{n}$ and it is desired to make a correct comparison to see if the point is really in or out of the true limits based on its particular sample size. It is fairly common practice to agree that when the subgroup size differs from $\bar{n}$ by more than 25% of $\bar{n}$, that particular sample point is a candidate for special consideration as to proper control limits, subject to the two conditions mentioned above. Of course, if the sample point plots close to the center line on the chart, it will generally not need special examination, because it is almost certain to be in control for any of the n's used in the calculation of $\bar{n}$.

Figure 9 shows the essential data needed to make a p chart with control limits based on average sample size. These data represent the percent of daily production rejected at a 100% inspection of a component part of an electrical device. The part was inspected for 5 quality characteristics, failure of the part to conform on one or more of these tests being a cause for rejection. The data give $\bar{p} = 14.1\%$, with $UCL_p = 19.1\%$ and $LCL_p = 9.1\%$ based on the average sample size $\bar{n} = 438$. Then $(1.25)\bar{n} = 548$ and $(0.75)\bar{n} = 328$, so subgroups over 548 and under 328 in size are marked with an asterisk on the data sheet. Investigation of these 11 cases quickly shows that only samples 4, 6, and 13 need be questioned. On computing the

Figure 9 - Data for a p Chart with n Varying

Sample No.	n	np	p(%)	Sample No.	n	np	p(%)
1	528	19	3.6	16	412	42	10.1
2*	626	93	14.9	17	378	59	15.6
3*	135	20	14.5	18	426	50	11.7
4**	720	68	9.4	19*	127	14	11.0
5	530	113	21.3	20	415	49	11.8
6*	296	18	6.1	21	457	82	17.9
7	451	74	16.5	22*	683	99	14.5
8	474	108	22.8	23	485	62	12.8
9*	559	83	14.9	24*	767	91	11.9
10	423	68	16.0	25*	229	25	10.9
					10943	1547	
11	412	91	22.0				
12*	290	32	11.2				
13**	184	14	7.6				
14	432	73	17.0				
15	504	100	19.8				

$$\bar{p} = \frac{1547}{10943} = 0.141 = 14.1\%$$

$$\bar{n} = \frac{10943}{25} = 438$$

$$1.25\bar{n} = (1.25)(438) = 548 \; ; \; 0.75\bar{n} = (0.75)(438) = 328$$

$$3\sigma_p = 3\sqrt{\frac{\bar{p}(1-\bar{p})}{\bar{n}}} = \frac{3\sqrt{(0.141)(0.859)}}{\sqrt{438}} = \frac{3(0.348)}{20.93} = \frac{1.044}{20.93} = 0.050$$

$$\left.\begin{aligned} UCL_p &= \bar{p} + 3\sigma_p = 0.141 + 0.050 = 0.191 = 19.1\% \\ LCL_p &= \bar{p} - 3\sigma_p = 0.141 - 0.050 = 0.091 = 9.1\% \end{aligned}\right\} \text{based on } \bar{n} = 438$$

For sample #4:

$$3\sigma_p = \frac{1.044}{\sqrt{720}} = \frac{1.044}{26.83} = 0.039 \begin{cases} UCL_p = 0.141 + 0.039 = 0.180 = 18.0\% \\ LCL_p = 0.141 - 0.039 = 0.102 = 10.2\% \end{cases}$$

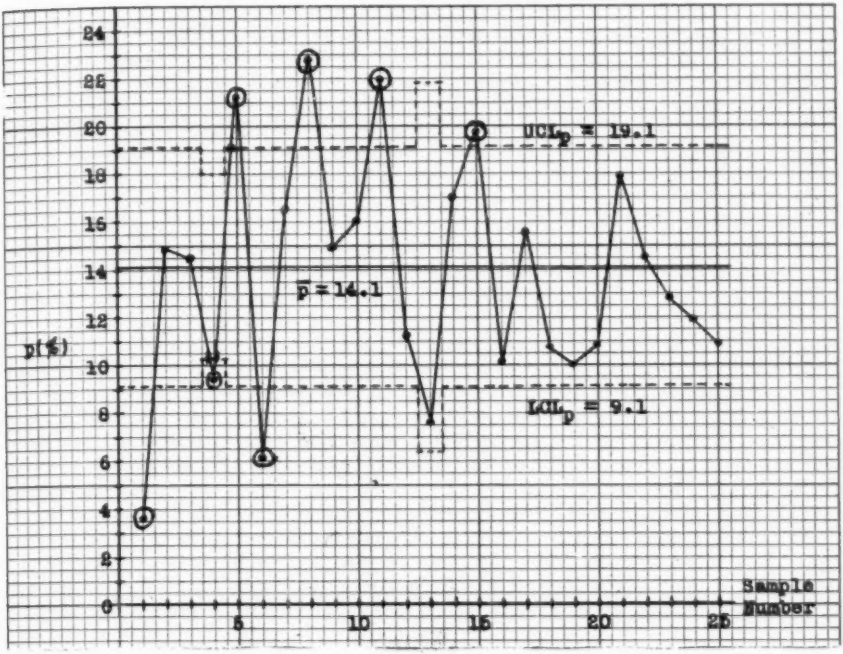
For sample #13:

$$3\sigma_p = \frac{1.044}{\sqrt{184}} = \frac{1.044}{13.56} = 0.077 \begin{cases} UCL_p = 0.141 + 0.077 = 0.218 = 21.8\% \\ LCL_p = 0.141 - 0.077 = 0.064 = 6.4\% \end{cases}$$

true limits for these three cases, it turns out that only #4 and #13 have limits that change the story. Based on $\bar{n}$ limits, #4 is within and #13 is outside the control band. Based on true limits relative to their respective sample sizes, #4 is outside and #13 is within the corrected control limits.

Figure 10 shows the corresponding p chart with $\bar{n}$ limits corrected for samples 4 and 13. The last 10 points are all in control at a level of $\bar{p} = 13.1\%$. If it can be anticipated that daily production will average close to 440 units per day, it would be reasonable to choose trial standards of $p' = 12.5\%$ and $n' = 440$, and set up a blank chart based on these standards for the next 20 to 30 samples.

Figure 10 - A p Chart with Variable Limits



If the points, as they are posted on the chart, seem to be conforming pretty well to the 12.3% level, it would be a simple matter to make such adjustments in control limits from day to day as are called for by the considerations we have been discussing. If the process shows a marked tendency to shift away from the trial standards, it would be wise to operate on process values, $\bar{p}$ and $\bar{n}$, until such time as reasonable evidence of stability in the process begins to show up.

In p chart work it is desirable to begin to operate on standard values as soon as possible, but with varying sample size, one has to be reasonably certain that the standard, p', is being approximated by the process in order to make correct decisions regarding points that are marginal with respect to control or that are based on sample sizes differing widely from the standard average, n'. The best way to learn how to make and operate a p chart based on variable sample size is to actually make and use one for awhile. If you can hold the sample size constant, by all means use an np chart. But where this is not possible, you will soon find that using a p chart with limits based on average sample size, and corrected as occasion requires, becomes just as routine and meaningful and helpful as any other of the Shewhart Charts.

The Number of Defects per Unit, or c Chart

Nature and construction of a c chart. How many defects could there be in a radio set, an automobile, an airplane, or a tractor? How many defects could there be in a roll of paper, a bolt of cloth, a mile of insulated wire, or a pane of glass? Theoretically, the answer to each of these questions is "Infinitely many." But if the manufacturing process that turns out these various articles is any good at all, how many defects in the examples cited do you really expect to find? The answer is, "Relatively few."

Now whenever the number of defects we expect to find in some unit of production is relatively small compared with the total number that could occur in that unit, we have a situation in which the appropriate control chart to be kept is the number of defects per unit, or c chart. The unit of production may be a sub-assembly, a final assembly, a length, an area, or a bulk. The essential thing is that the unit, whatever it is, must be potentially capable of possessing an indefinitely large number of defects. Quality for this unit is then measured by counting the number of specified kinds of defects actually observed by an inspection of the unit. The fewer the number of defects found, the better the quality. The defects themselves may be measurable or visual; all we do is make the appropriate test and put down a tally mark if the defect in question is found to be present. The inspection may be for just one defect or for several. Thus, we may count all the defects found at a final inspection of an airplane, or we may wish to keep a separate record of the number of missing rivets observed at this final inspection.

Once the unit of production, or "area of opportunity" for the occurrence of a defect, has been defined, and the type of defect (or defects) to be looked for in this unit has been specified, we are ready to begin inspection and collect data. The data sheet for a c chart is particularly simple. All it needs, in addition to an appropriate heading, is a column for sample (or unit) identification, a column for the number of defects found, and provision for remarks or comments that would serve to supplement the data in certain cases. If more than one defect is covered by the inspection, provision should also be made on the data sheet for a breakdown by type of defect similar to that shown in Figure 1 for the enamelling process.

Figure 11 shows the essential data from a record form for a c chart. These data were collected at a sub-assembly inspection station in the production of a radio set. The "unit" of production inspected consisted of 5 partially assembled sets. The number of defects, or c, column includes defects of all types observed at the inspection. The breakdown by class of defect is not shown. Thus, sub-assembly unit #1 consisted of 5 sets on which a total of 77 defects of all types were found; sub-assembly #2 consisted of another 5 sets on which a total of 64 defects of all types were found, and so on.

The reason for using 5 sets as the inspection unit rather than a single set will be explained presently. The point to remember, however, is that we are not dealing with a sample of 5 in this problem, but rather with a single unit of production which consists of 5 sets.

Figure 11.

Number of defects (all types) found at sub-assembly inspection of radio sets; 5 sets = 1 inspection unit.

Sub-Assembly No.	No. of Defects	Sub-Assembly No.	No. of Defects
1	77	26	26
2	64	27	23
3	75	28	9
4	93	29	15
5	45	30	63
6	61	31	39
7	49	32	58
8	65	33	61
9	45	34	59
10	77	35	51
11	59	36	33
12	54	37	40
13	41	38	40
14	87	39	46
15	40	40	32
16	22	41	46
17	92	42	49
18	89	43	31
19	55	44	36
20	25	45	41
21	54	46	49
22	22	47	39
23	49	48	49
24	33	49	43
25	20	50	43
	1393		1021

Summary

Points 1 - 25

$\bar{c} = \frac{1393}{25} = 55.7$

$\sqrt{\bar{c}} = 7.5$

$3\sqrt{\bar{c}} = 22.5$

$UCL_c = 78.2$

$LCL_c = 33.2$

Points 26 - 50

$\bar{c} = \frac{1021}{25} = 40.8$

$\sqrt{\bar{c}} = 6.4$

$3\sqrt{\bar{c}} = 19.2$

$UCL_c = 60.0$

$LCL_c = 21.6$

For the next 25 points, adopt trial standards $\begin{cases} c' = 36 \\ UCL_c = 54 \\ LCL_c = 18 \end{cases}$

The distinction may seem academic, but it is not: there is no such thing as sample size, n, in c chart work, there is only a specified unit for inspection purposes, and it is the number of defects observed in this unit that counts. Sometimes, as in this problem, it is desirable for purposes of getting a useful c chart, to lump together several of what might be considered "natural" production units to form a single inspection unit. No matter how you choose to regard it, what you always get in a case like this is the number of defects per unit, not the number of defectives per sample.

The center line on a c chart is designated as $\bar{c}$ and defined by

$$\bar{c} = \frac{\text{total no. of defects observed in all units inspected}}{\text{total number of units inspected}}$$

Figure 11 shows the value of $\bar{c}$ for each series of 25 inspection units. There is no objection to saying, for instance, that the number of defects per set averaged 11 over the first 125 sets inspected, but the chart will be concerned with an average of 56 defects per unit of 5 sets over this run.

Control limits on a c chart are given by the formulas $UCL_c = \bar{c} + 3\sqrt{\bar{c}}$ and $LCL_c = \bar{c} - 3\sqrt{\bar{c}}$. These are particularly simple formulas to use. They set limits within which the number of defects per unit can be expected to vary from unit to unit if only causes of variation natural to a process operating at a level of $\bar{c}$ are present. They are 3-sigma limits, so it follows that $\sigma_c = \sqrt{\bar{c}}$. Figure 11 shows the values of these limits for each series of 25 units inspected.

It is always an advantage to have a lower limit on an attribute chart when possible. Points outside a lower limit may lead to the discovery of ways to improve quality, and they always serve as a check against relaxation of inspection standards. From the formula for LCL_c it is easy to see that LCL_c will be greater than zero if $\bar{c}$ is greater than 9. However, $\bar{c}$ equal to or greater than 15 is better, because then LCL_c is 3.7 or more, so that there is some elbow room between zero and the LCL_c. This is the reason 5 sets were taken as the unit for the radio set c chart. With the unit chosen this way, the chart has a useful lower limit; with a single set as a unit, the lower limit would be too near zero to be useful as a control limit.

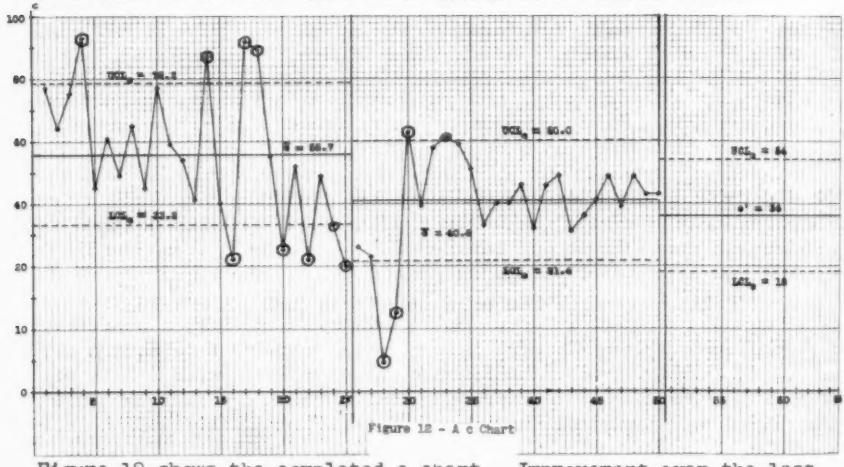


Figure 12 - A c Chart

Figure 12 shows the completed c chart. Improvement over the last half of the chart is evident. Assuming that inspection standards have not relaxed, the chart shows the process operating in good control from the 34th point on. Whether or not control at this level is satisfactory depends on cost considerations as discussed earlier in this paper. At any rate, the chart shows a trial standard set at $c' = 36$. If this is a satisfactory standard, attention should then be focused on maintaining control at a level somewhere between

c' = 36 and 40 , regarding any further improvement in process level as a by-product of the effort to maintain control rather than as a primary objective.

Perhaps there are not as many opportunities to use a c chart in quality control work as there are for the other types of Shewhart Charts. Nevertheless, a c chart provides an effective instrument for charting variations in quality whenever quality is to be measured by counting the number of defects observed in some suitably defined unit of product rather than by counting the number or ratio of defective pieces found in a specified group, or sample, containing several pieces of product.

Supporting theory for attribute charts. The mathematical model on which p and np charts are based is known as the Point Binomial, or Bernoulli Distribution. Its properties are obtained by working with the expansion of the expression $\left[(1 - p') + p'\right]^n$, where p' = universe, or standard, fraction defective for a process in control, and n = constant sample size. Its graph is step-shaped, like a histogram, rather than a smooth curve, like the normal curve. The formulas for the control limits on p and np charts are a direct application of the standard deviation property of this theoretical distribution. The zone between the 3-sigma limits for this model does not, in general, contain 99.7% of the total variation as is always true of the normal curve model. Nevertheless, these limits include enough of the total variation to make them very useful in application for distinguishing random from assignable causes of variation.

The mathematical model for the c chart is known as the Poisson Exponential Function, whose explicit formula we shall omit here. It is a limiting form of the Point Binomial under the assumption that p' is very small, n is very large, and np' is a number relatively near zero. In this case, neither n nor p' is known; all that is known is the product np', and this product is called c'. The graph of the Poisson model is also step-shaped rather than a smooth curve, and, in general, is noticeably unsymmetrical. When p' is less than 0.05 and n is greater than 10, the Poisson formula gives a very good approximation to the terms of the more exact Point Binomial model. It is thus a very useful piece of machinery to have around for approximation purposes. Rather complete tables and alignment charts have been created based on the Poisson function, and these are very useful in certain applications, particularly those dealing with acceptance sampling. (See Ref.1, p.240 and Table G, p.542.)

Anyone with a flare for mathematics will find a treatment of the Bernoulli and Poisson functions in any good textbook on mathematical statistics. A very readable discussion, which is not too technical despite the fact that it must necessarily involve mathematics, is available in Ref.1, Chapt. IX.

Conclusion. It has only been possible to "hit the high spots" in this presentation of the subject of attribute charts. I hope enough has been said to suggest that they are a fundamentally simple and

widely useful form of control chart, easy to keep, and easy to explain to shop personnel. They give the beginner a tool with which he can immediately start experimenting with quality control in a way requiring no special equipment or change or interruption in current plant procedures. Like a faithful hunting dog, they can often be used, even by a novice, to "smell out" hitherto unsuspected sources of quality trouble in a production process. Thus exposed, the sharper tools of measurement charts can often be put to work on such sore spots with telling effect in quality improvement.

For those of you who are interested in exploring this whole subject of attribute charts more thoroughly, one of the best, most readable, and most comprehensive treatment currently available will be found in Chapters IX, X, XI, and XV of Ref.1. Ref.2 is also recommended as a source worth consulting.

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APPLICATIONS OF CONTROL CHARTS IN INDUSTRIAL QUALITY CONTROL

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With the background of the last two papers in this series, you will now be in good position to understand the applications of control charts as discussed in this paper. The headings are given in general terms to encourage you to think of applications in your own plant. Although the illustrations presented must of necessity be specific, the principles which made them successful are widely applicable. If you can follow through this presentation and fail to get any new ideas on the problems in your own plant you must be lacking in imagination or in hours of sleep the previous night.

In the following case studies but very little mention is made of the men who made these excellent applications. Their names have been largely omitted in the interest of brevity and to focus attention on the principles used. The references at the end give further facts on the men, and the jobs they did. Also the applications have been oversimplified here in order to stress the essence of the problems. With these points in mind we shall proceed with the eighteen types of practical application.

1. Process Control. At Cap de la Madeleine, Quebec, a foundry of Electric Steels Limited was having much trouble with a high manganese steel shoe for tanks. (1)(2)* The over all rate of rejection of castings was averaging around fourteen per cent, with rather wide swings. As a control chart program was introduced, past date were used wherever possible, but some changes were necessary, such as gathering as much data as possible on a heat basis. Eventually about one hundred different control charts on some sixty characteristics were carried. These included analyses, sand variables, melt and pouring practices, and product rejection (as to kind of trouble).

Whenever any chart showed a point out of control, this was an indication of a change in the process somewhere. By tracking down the reason for such changes it was possible to make the whole foundry practice more stable. The charts also helped in another way through showing relationships. For example, if the average point for silicon content was below the lower control limit, while the corresponding point for percentage of gas holes was high or beyond the upper control limit, there would be some indication of a relationship. Occurrence of high silicon and few gas holes would strengthen the conclusion. Such relationships were further studied by a statistical technique for analyzing contingency tables.

As the control of the foundry process improved the over all rejection rate (all causes) dropped from a level of about thirteen per cent in January to about two per cent in October, even though production had greatly increased. Careful government records credited $300,000 of savings to a cost of $15,000 for the program over a period of eighteen months.

* See references at end.

Figure 1 shows the picture of rejects on railroad car side frames in another plant as a similar control chart program took hold.

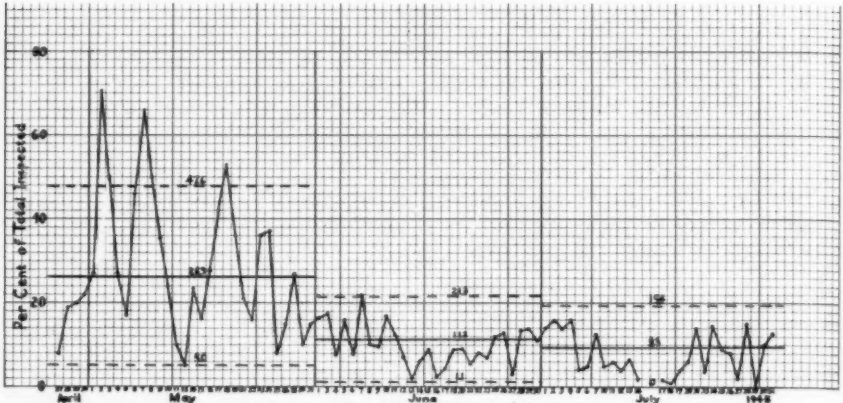

Figure 1 — Per Cent Rejection, Side-Frame Castings — Dominion Foundries and Steel

A second illustration of process control is a simple one. A check of silicon in steel showed good statistical control, after straightening out an irregularity in the collection of data. However, the level was higher than was necessary to meet the specifications of .20% to .28%. Because the process was running in good control it was perfectly safe to shift the level slightly downward thereby saving over $2500 of ferro-silicon mineral per month. This control chart job took four hours of one man's time to complete it!

2. Fraction Defective - Tank Leaks. Leakage on jettison fuel tanks was causing much trouble and cost. (3) Charts were run on the total fraction defective from all causes and also charts for each of the most troublesome causes of leaks. The control charts gave a clear indication when the various operations were out of control. They also helped to determine when the cause had been found by showing points back in control. Some of the factors having the greatest influence on various operations were wear on welding fixtures, sizes and quality of silver solder, shifting of operators because of absentees, operator technique, cold working of metal, type of plating on sheet metal parts, and inspection procedures. Figure 2 shows the record or progress on filler neck leaks. Just the plotting of the chart day by day was a powerful influence for an improvement.

3. Filling Operations. In the filling of containers with fluid, inventory showed that a large loss was taken each month because of lack of control of the process. It must be obvious that the greater the variation in the amount of material loaded or packed in a container, the farther above the lower specification you must aim to be on the safe side. William Tell could not have used a shotgun to knock the apple off his son's head! Moreover, any significant tendency to a lack of statistical control will always give danger of not meeting the lower specification, no matter where the average level is. Figure 3 shows the first preliminary run of twenty-five samples. Lack of

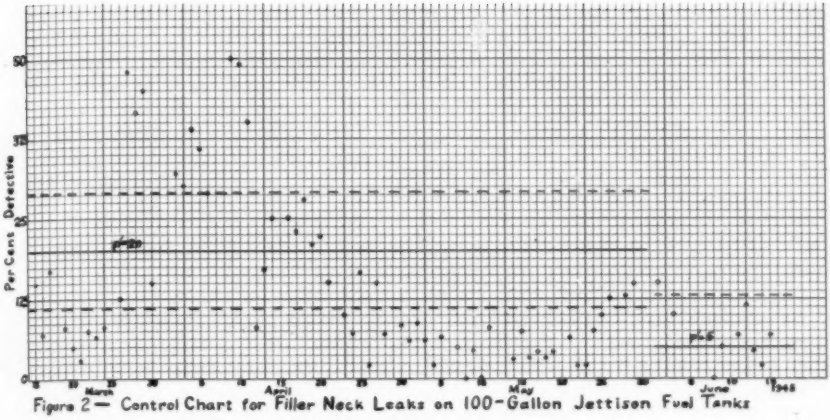

Figure 2 — Control Chart for Filler Neck Leaks on 100-Gallon Jettison Fuel Tanks

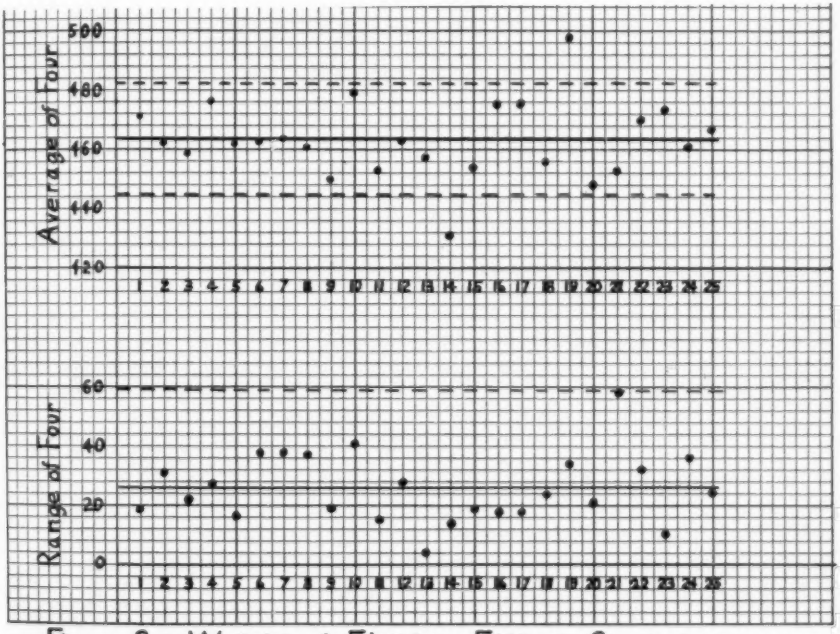

Figure 3 — Weight of Fluid in Filled Container

control of average level is indicated on subgroups 14 and 19, while the process became excessively variable or sloppy on subgroup 21. Some of the assignable causes pinned down in the course of the investigation

were lack of pressure control, lack of temperature control, obstruction in tubes, improper timing cycle, and personnel and calculation errors. Within only three months control had been improved to such an extent that a savings of $13,000 of fluid per month was being made as compared with earlier filling operations. In other words, in order to safely meet the lower specification, they were able to steer the level enough closer to this minimum to save a difference of $13,000 worth of fluid. This was the great bulk of the excess per month which they were not being paid for but which they had been shipping each month in order to meet the minimum. The decrease in variability and improved control were the essentials to this saving.

4. Getting More Out of Present Equipment. Two thirty-year old Cleveland machines were considered almost as valuable as scrap iron as they were as machines.(4) Product from them was much too variable to be of much use. The important point, however, was that the average range indicated that if the assignable causes of the bad control could be found and eliminated, the machines would then do fair work. Lack of control was therefore a definite sign of hope for improvement. A chart helped find two assignable causes on one machine after which it ran in control for two and a half days. Two or three more items needed attention and a continual improvement was shown. Moreover, the "natural variability" of the machine was more than cut in two and it was staying in control. The result was that instead of junking these old machines it was found that they could do any but the closest jobs. You may say that such troubles as they found should have been found by any competent man. The emphasis on getting the two machines into first class repair had been ineffectual until the charts were used.

5. Meeting Tight Specifications. Extremely high precision work is necessary in manufacture of the Norden Bombsight. (5) Whole departments were working on total tolerances of from two to one ten-thousandth of an inch. Fraction defective charts by department, by type of machine, and by part served to indicate where the greatest trouble was being encountered. Measurement charts were then used for trouble shooting in these spots, and as such proved a powerful tool. Some simplified charting procedures were worked out. Two important special advantages of the statistical approach were the help in breaking in new personnel and the emphasis upon running to the mean. The latter gives less plug gage wear, easier assembly, and although it may very slightly increase the number of rejects, it makes large savings in the cost of rework. Also, the capabilities of various machines were determined. Monthly rejections decreased from about seven per cent to one and a half per cent in ten months.

6. Aid on Random Assembly. The ideal in manufacture of interchangeable parts is that any one piece of one type should fit any one of the mating type. In an interesting paper,(6) Martin A. Brumbaugh showed some comparisons of pieces from a pre-war inventory and the initial post-war production of the same parts. Variability of the former is so great that a large proportion of the pieces were out of blue print specifications. The great decrease in variability to the post-war product is such that the expensive fit-and-file assembly procedure can be replaced by random assembly of one piece with any other. See Figure 4, which compares the frequency distribution of

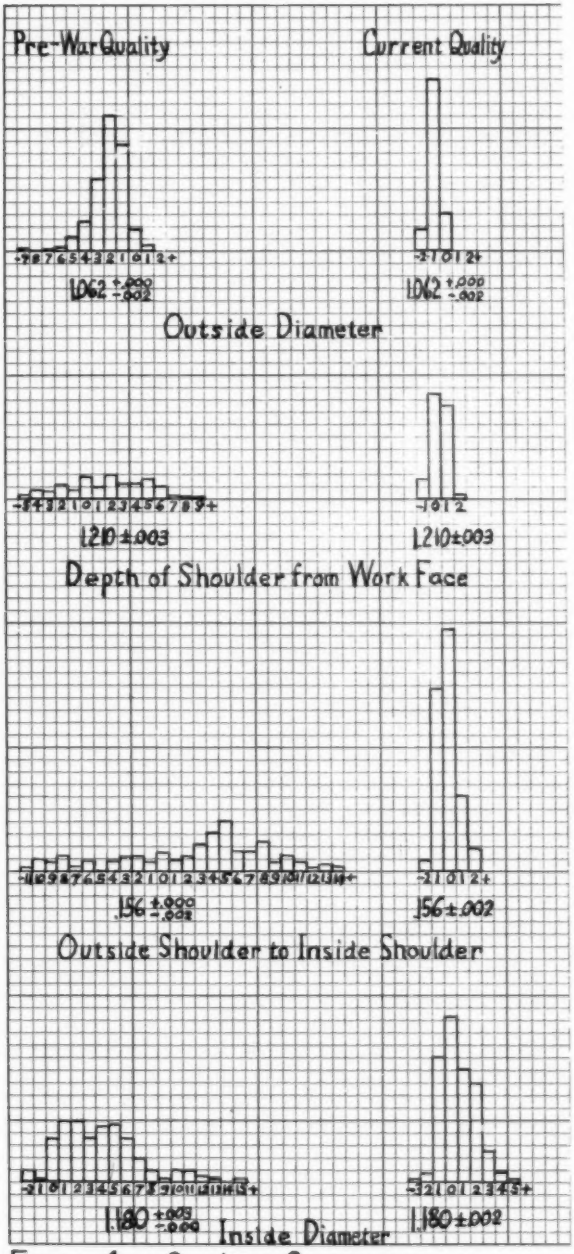

Figure 4 – Quality Comparison

four types of parts pre-war and post-war. (A frequency distribution tells how many of each different size there were.) A big reason for the improvement was the installation of a control chart program in the plant.

7. Prediction of Maximum Moisture Content. Douglas W.Ferris, of Nickey Brothers, Memphis, Tennessee, who is giving one of the clinic talks at this conference, devised a technique for improved operation of kiln drying of hard wood. Kilns are usually set to dry the right length of time for the wettest lumber in the lot, in order to avoid honeycombing. Prediction of this maximum moisture content has been the stumbling block. Ferris' method is to take six measures per stack and estimate the maximum wetness for this stack. Then a number of stacks with similar maximum wetness are placed in the kiln at the same time and dried according to the composite picture of their moisture content. In this way 500,000 more board feet per month are going through each kiln. Moreover, where before there were customer complaints on practically every carload, there were only 23 claims filed in 5 months, and none had to be paid! The quality control department is becoming a training ground also, some jobs being learned there in a few months which formerly required fifteen years.

8. Sound Handling of Laboratory Data. All kinds of laboratory data should be subjected to control chart study. If a point is out of the control band on the average chart, then this is an indication of a change in the laboratory conditions for the corresponding sample. Until the assignable causes for all out-of-control samples are isolated, the whole mass of data is suspect, and the average of all results is not to be trusted. This is a searching but necessary check in standardizing procedures.

If a point is out on the range chart then the test method is lacking in reproducibility or the material is not homongeneous. It could also be a difference in personnel.

The average range for a series of homogeneous samples on the same material provides a direct way of obtaining the all-important measurement error. Particularly with any new testing machine, such as one for measuring tensile or bending strength of paper, or permeability, or surface finish, we want to know whether it gives reproducibility and how large a measurement error it has. Control charts are a direct help on this and on the design of new tests.

9. Chemical Data. Control charts for measurements are a "natural" for chemical data. Analyses, physical properties, calibrations, combustion data, and batch per cent spoilage are all typical data where control charts can help. A number of examples are described in a recent article by Wernimont.[7] Random errors are especially noticeable and important in chemical data, and hence, so are statistical methods for controlling them. Anyone in this field must have noticed the expanding literature on the statistical approach in chemistry, and this is just the beginning.

10. Checking Inventory. A company with a large stock of machined pieces became concerned about the quality of its inventory. In this study it is only natural that sampling would be desirable if at all possible. Control charts served to tell the presence or lack of control and to aid in deciding how much to sample. A much smaller sample is sufficient if there is control. Here is an example of management wanting to get at the facts regardless of how they come out.

11. Safely Decreasing Amount of Inspection. In the manufacture of .50 caliber armour-piercing ammunition one of the tests was for accuracy.(8) The measure of accuracy was the average distance from the center of fire on a target to each of the ten bullet holes. A large amount of inspection was conducted with a view to assuring satisfactory performance. Inefficient use was made of past data, however, since the production of each shift for each machine tended to be regarded as a lot by itself, inspection being continued on each "lot" until a decision could be reached. By the use of a slightly modified control chart, it was found that the product was in good control in almost all cases with regard to accuracy. Hence as long as this continued to be the case performance of past production gives an excellent guide as to what future production will be like. A greatly reduced amount of inspection is therefore justified since its main aim is no longer to decide on just this one lot of product, but is rather to check whether there is evidence of a change in conditions. In this way hundreds of dollars of inspection time and material were safely saved every day.

12. Clerical Errors. An interesting application of a simple control chart was made at a mail order company. (9) Clerical errors are a continual source of expense and trouble. A chart on the number of errors found on samples of 100 tickets was plotted and studied. Initial results showed 3% of the tickets with errors. A goal of 1.78% was set and 1.65% attained in the latter part of the first month. The next month the average level reached 0.7%. The large, conspiciously placed chart was a powerful psychological factor. The opening applications were so successful that the use of charts is now virtually company wide.

13. Changing Specifications. The control chart is a powerful tool for working to a specification. When the chart shows lack of control, then, before asserting that specifications cannot be met, one should get after and eliminate the assignable causes whose presence the chart has indicated. Often times it will then be found that the specifications can be met, perhaps very easily. One such case was a plant whose product from both the day and night shift was just too variable, and hence a request for a wider specification was made and granted. However, a control chart showed that the "natural variability" of the process would have permitted meeting the original specifications. One of the shifts was working at a level much higher than the other. The combined product was too variable, but when the discrepancy was adjusted the old specifications were readily attainable.

The situation is entirely different, on the other hand, when the production and inspection process gives a picture of good statistical control. The conclusion is then that the machine is doing just about

all that you can expect of it. There are only three things you can do.

1. Ask for a relaxation of specifications.
2. Make a rather fundamental change in the process, such as getting a new machine.
3. Inspect the product 100%.

A bid for the first of these, which is the most inexpensive of the three, should always be supported by a control chart. Until your control chart shows the process to be in statistical control you just do not know whether or not specifications can be met.

14. Aid on Design Specifications. Control charts give the design engineer an excellent guide as to what tolerances current equipment can be expected to meet. Thus they can have a better economic approach and will know better the cost of specifications. If there is really needed a tighter specification than any machine is capable of giving, then it will be known in advance that 100% inspection will be needed, or a new process. Only where absolutely necessary will such tight specifications be drawn. This approach is a realistic one and will help avoid the common situation of the designer dividing in two the tolerances he really needs, and the production man promptly doubling the blue-print tolerance.

15. Destructive Testing. Control charts provide the only sound approach when inspection must of necessity be destructive. Aid in tracking down assignable causes is given. Moreover when, and only when, there is statistical control can one be sure of the quality of the uninspected portion of the product.

16. Sub-Assemblies. Many applications have been made on "squawks" or "crabs" found in the inspection of sub-assemblies. The c-chart is the natural approach. A record of improvement is shown in Figure 5.

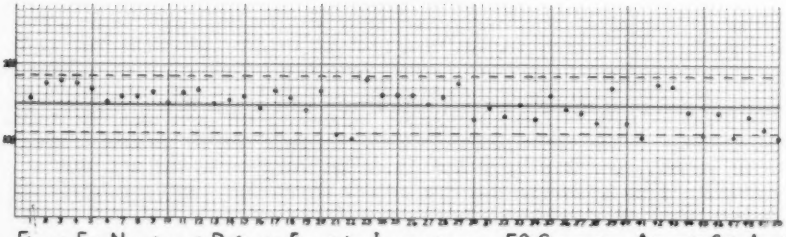

Figure 5 – Number of Defects Found by Inspectors on 50 Successive Aircraft Sub-Assemblies

Even without control limits the chart gives incentive toward improvement. The limit lines are direct guides to action for both high and low points. The aircraft industry took a leading place in successful applications of this type.

17. Acceptance by Control Chart. During the war the Aberdeen Proving Ground was deluged with armor plate for testing. The velocity

of penetration test was extremely expensive. On the basis of eight samples of four tests each (a minimum of preliminary data) a producer would go on reduced sampling if his armor plate showed statistical control at a satisfactory leve. Control and level were both closely watched. Here was an example of scientifically unbalancing the amount of inspection. The less reliable product was given more inspection and the more reliable less inspection, instead of inspecting it all the same amount. Thus was the inspection of armor plate expedited more safely, by statistical control.

Another type of acceptance using control charts is the "grand-lot scheme" of Simon. (10) Because inspecting each lot as it comes and deciding on it without regard to other lots from the same supplier requires big samples, Simon suggests the following scheme. Consider together a number of lots which for engineering reasons would seem to have come from the same general conditions of manufacture. Take a moderate sample from each. Check these samples for consistency of average and of variability. If there is good control at a satisfactory level accept all the lots. If, however, one or more of the lots seem to differ from the others as shown by out-of-control points then more evidence must be gathered on each such lot until a decision can be reached. Thus, when there is control the evidence from the other lots can be counted in checking a given lot, but when lack of uniformity is shown then the suspected lot must be given a thorough check. This scheme is valuable whenever practical conditions make it possible.

18. Factors of Safety. Although I can point to no specific application, it seems to me that the problem of safely reducing a factor of safety is strictly analogous to the filling operation. If assignable causes of variability can be found and removed so that the product can reach a state of statistical control, then the greater predictability of the upper and lower limits of strength plus the probable decrease in natural variability in the product should make possible a sizable decrease in a factor of safety. Control charts are a "natural" for this job.

Concluding Remarks. You may well be wondering why the inspection departments were not more in evidence in these applications. They were in on most, if not all of these applications. In practical quality control, however, the main emphasis is not on having the inspection department sort the good from the bad, but rather to have inspection aid in improving the process. Properly handled inspection data can provide a basis for action on both the product and the process. In most of these cases inspection was working hand in glove with production as a team and not as combatants. As Schmid says (5) "Quality is put into a piece at the machine - not in the inspection crib."

Well gentlemen, and ladies too, the problem is yours. This new tool is universally applicable to industrial products. How well it works for you will depend upon your knowledge of the processes, your industry, your ability to get along with people, your common sense, and above all, your imagination.

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FUNDAMENTALS OF ACCEPTANCE SAMPLING

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Why Sampling Inspection? The answer to this question is: to save you money. Inspection of every single piece in the lot is a nice comforting thing. It may make your accounting department happy to think that, through 100% receiving inspection, they are not paying out money for any bad pieces (provided your inspectors have not missed any bad ones!) But your company is getting a sorry bargain, if the cost of 100% inspection, over and above what a good sampling plan would cost, is ten times the expense the acceptance of a few additional bad pieces would cause. Make no mistake about it, if you absolutely have to have all good pieces on which to work you simple cannot use sampling inspection. But if you can afford to accept, say 5% bad pieces or 2% or 0.3% bad then you can use sampling. Moreover, if inspection of a characteristic must be destructive, such as tensile strength of bolts, then you have to use sampling inspection whether you like it or not.

Just consider the stupendous job of the Army and Navy during the war in accepting tens of billions of dollars worth of goods. Had every single article been inspected before acceptance, our armed forces would still be fighting the war. The plans used for all this task of acceptance were scientifically worked out to provide whatever protection was needed and yet to do the job as economically as possible.

Unless you are using scientific acceptance of material in your plant you are probably well out on a horn of the dilemma of acceptance: Either you are inspecting far too much product before making a decision for acceptance or rejection, or else you are making a decision on inadequate evidence, and often reject material which you really want or accept material that is not satisfactory. Either of these errors may be costing you a sizeable sum.

What is Scientific Acceptance Sampling? If we can get but one idea across in this paper, let it be this: Know what your risks are and learn to control them at economic levels. A sampling plan can be designed to do just about whatever you want it to do. If you would not mind having 1% of the incoming pieces defective, but 4% would be too high, you can arrange for this. It is easy to find a plan which will insure that, if lots come containing 1% of the pieces defective, you will nearly always accept such a lot, but if one is sent you which contains 4% of its pieces defective, then there will be very little chance of its being accepted. The most economical plan in a practical situtation is usually a compromise between risks and amount of sampling. You want a small risk and you also want a small amount of inspection. Before deciding on a plan you should know what risks it will involve and the amount of inspection it will require.

An Unscientific Plan. One of the commonest misconceptions in acceptance sampling is that by sampling a fixed percentage of the product we shall have a good plan. If you or any of your associates are harboring this germ we hope that the following inoculation will prove effective.

First let us suppose that we are being sent for inspection, lots of fifty pieces each, and that we are addicted to "ten-percentitis". Hence, since we make a decision on a lot from a ten per cent sample, we choose but five pieces from the lot and inspect these. Now let us assume that we are aiming at accepting lots of 1 per cent or better, but do not want lots much worse than say 4%. We decide therefore to reject the lot of 50 pieces if we find any bad pieces in the sample of five, and we accept the lot if the five are all good. This may sound as though we are being "tough", but let us see. In Table 1 are tabulated the chances of acceptance of a number of different lot qualities. Thus if all 50 pieces in the lot are good, then the lot fraction is 0%, all five pieces in the sample are of necessity good, and hence the chance of acceptance is 1.000, i.e., certainty. In the second row, if there is one bad piece in the lot, the lot fraction defective is 2%, and by an appropriate mathematical calculation there will be 9 chances in 10 that the lot will be accepted, and so on.

Now are we being "tough"? If a lot which is 10% defective is offered us, it will have over half a chance of being accepted, while if the lot is 30% bad it will still have over one chance in seven, or so, of being accepted. Obviously we are not getting much protection against acceptance of bad lots. Moreover we are going to be running a risk of one chance in ten of rejecting a really good lot, namely one that is but 2% bad. Hence such a plan is not going to afford adequate protection to the consumer against acceptance of a bad lot, nor to the producer against having a really good lot rejected.

Lot % defective	Chance Lot will be accepted
0	1.000
2	.900
4	.808
6	.724
8	.646
10	.577
12	.513
14	.454
20	.311
30	.153
40	.067

Table 1 - Lots of 50, n = 5, c = 0.

Next let us suppose that we are receiving lots of 5000 pieces from another producer. In our rigid 10% program we therefore choose 500 pieces as a sample and inspect them. If the sample yields 2% or less of defective pieces, then we accept, if over 2% we reject. Since 2% of 500 is 10, this will be what we call the acceptance number, c, in the sample of 500 or n pieces. Ten or fewer bad ones in the sample call for acceptance, 11 or more for rejection. Now look at Table 2 to see what we are getting from our 10% plan. This plan will really distinguish 4% defective lots from 2% or 1%. We have real protection here, because the producer who sends 1% defective lots will have no trouble passing them, and we shall never have much trouble from 4% bad lots which have slipped by. But do not be too happy yet. Do you really need all of that

Lot % defective	Chance Lot will be accepted
0	1.000
1	.992
2	.582
3	.104
4	.008

Table 2 - Lots of 5000, n = 500, c = 10

extreme protection? If you really do, then there is nothing for it, you simply must have about 500 in a sample. On the other hand it is highly probable that you do not need to make such fine discriminations. If, for example, you could afford to take about a .10 risk of letting a lot which is 4% defective get by, and also could accept a risk of .05 that a 1% defective lot would be rejected, then the plan n = 200, c = 4 would be your plan. Thus if you are willing to loosen up on the risks a bit you can cut the sampling to 200 pieces instead of 500. Does it begin to be apparent then that some knowledge of the risks and how they vary with size of sample is a great help and will enable you to do a better job than if you rather blindly take 10% of all lots (or any other fixed %)?. In summary one may say that the gross size of your sample is of much more importance that the proportion of the lot you sample. Thus a random sample of 150 pieces gives about as reliable an indication on a lot of 5000 pieces as it does on one of 500 pieces.

The Operating Characteristic Curve. A great aid in visualizing how a sampling plan operates is the so-called "operating characteristic curve". In Figure 1 we see the two "OC" curves for the plans discussed above. Thus in curve (a) if the incoming lot of 50 pieces contains 3 defectives, it is a 6% defective lot. Find this figure on the horizontal scale, go up to the curve above this point and read over to the vertical scale, where we find that such a lot has about a .725 chance of acceptance. Note how this checks with Table 1. A 24% defective lot has, in similar fashion, a .23 chance to be accepted, etc. The poor operation of the sample of five is shown by the slow, gradual drop of the curve toward the quality axis. It rejects a fair sprinkling of good lots (1 in 10 at 2% defective), but will accept about half of all lots as bad as 12% defective. Hence it does not adequately discriminate bad lots from good lots.

Next examine curve (b). Note that a 1% defective lot is almost certain to be accepted, a 2% defective lot has about a .60 chance of acceptance, while a lot 3% defective is only going to get by about .10 of the time. The square shoulders and steep drop of this curve means that it distinguishes sharply between good and bad lots. You can have a sampling plan with just as square shoulders and sharp discriminating power as you wish, provided you are willing to pay for as much inspection as it will require. The larger the sample the sharper it will discriminate, but the more it will cost for inspection. You want to stop at the most economical point for your own plant conditions.

A Scientific Plan - Single Sampling. There is no one "best" plan for all possible cases. You will simply have to pick a plan which seems adequate to your own particular needs. Fortunately you will not have to do your own calculating but can choose from among the many which have been devised. Among these are the Army Ordnance tables (1), the Navy tables (2), and the Dodge-Romig (1) tables.

As an illustration we shall take the case where the acceptable quality level is .5%, and unacceptable lot quality is 5% defective. Each lot contains 600 pieces. A single sampling plan for such a

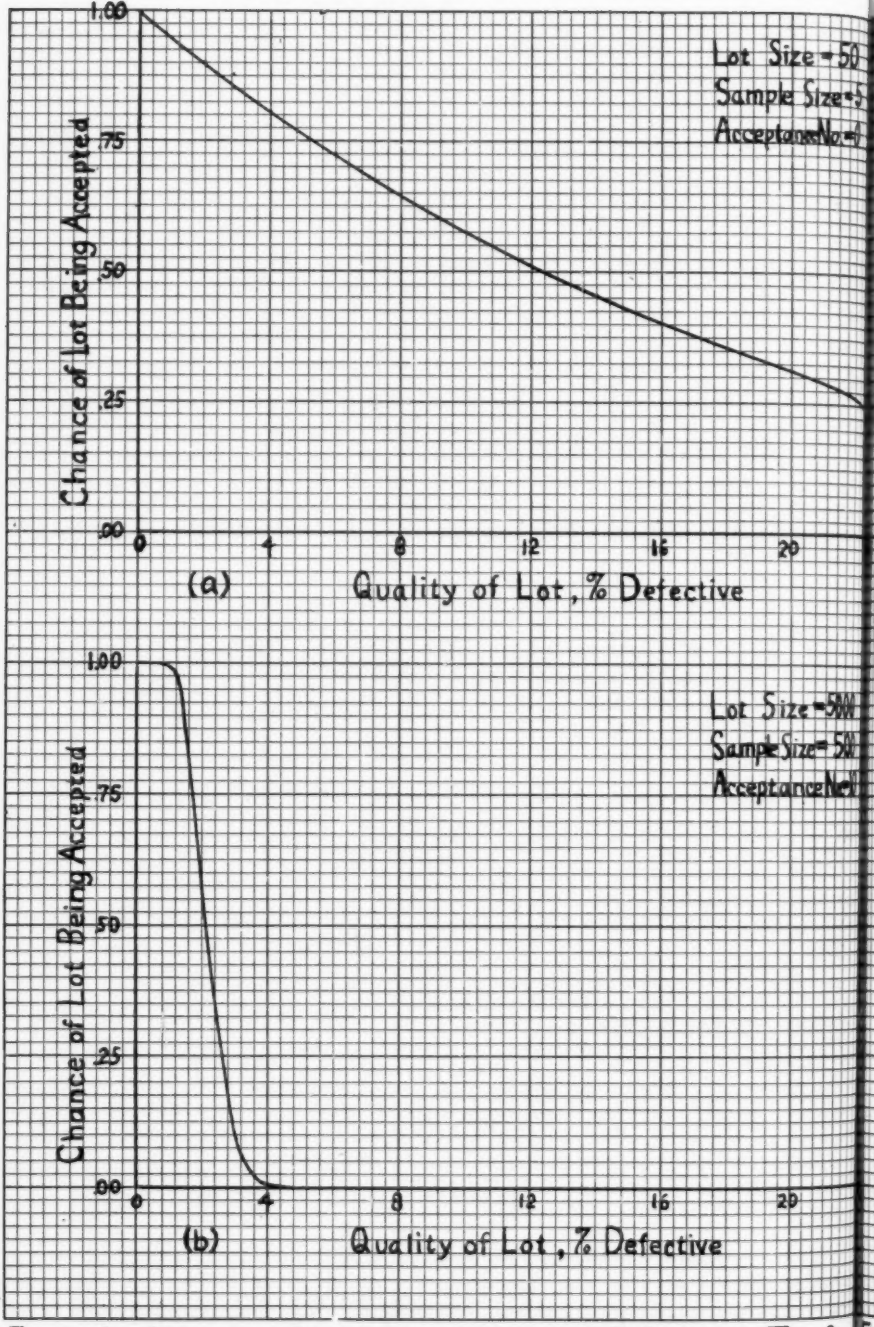

Figure 1 - Operating Characteristics of 10% Sampling, Two Cas

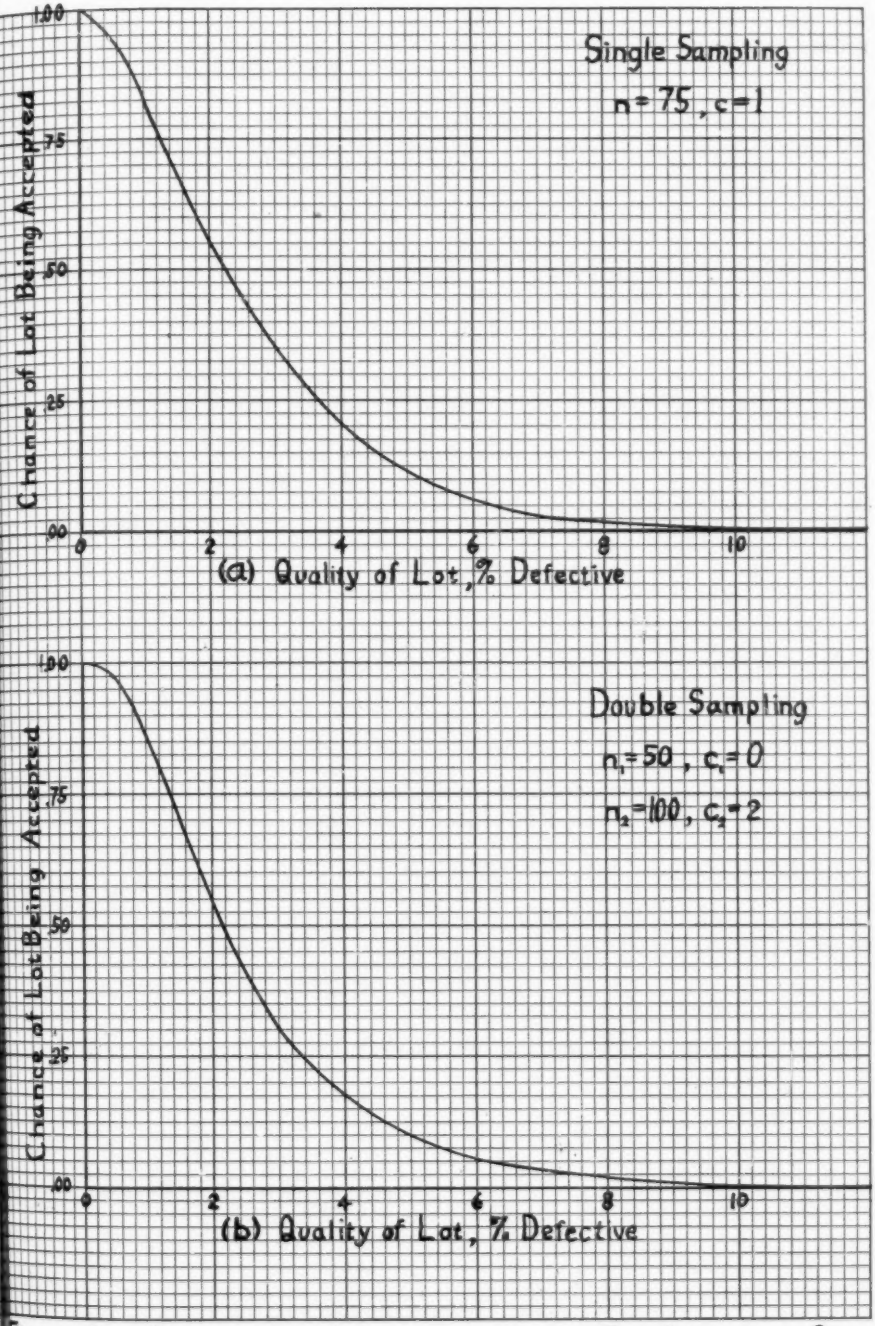

Figure 2 – Operating Characteristics, Two Standard Plans

situation is one calling for samples of 75 pieces each and an acceptance number of 1. Thus if the sample contains 0 to 1 defective pieces the lot is accepted, otherwise it is rejected. This plan may be found in either the Army Ordnance Table or the Navy Tables. The way in which this plan operates on lots of various qualities may be seen by reference to Figure 2 (a). From this curve we can easily see that the chance of acceptance of a lot which is 5% defective is only about .11 or .12, while the chance of acceptance of a lot which is .5% defective is about .95. These two figures are often described by saying that for this plan

(a) the consumer's risk of acceptance of a lot which is 5% defective is about .11, and

(b) the producer's risk of rejection of a lot which is only .5% defective is about .05 (that is, 1.00 minus .95).

The consumer's risk is the important fact about lots of poor quality and the producer's risk is crucial on lots of good quality. It is natural to decide from practical considerations what percent defective (such as .5%) we shall call "good quality" and what percent defective (such as 5%) we shall call "poor quality". Secondly we are at liberty to decide what shall be the risk of rejection of "good quality" (.05 in our example), and the risk of acceptance of poor quality (.11 in the example). These four facts will then determine a single sampling inspection plan. If the amount of inspection called for to supply such protection is too great, for economic operation, then we must be willing to accept larger risks, that is, we must be willing to accept a less discriminating operating curve in the interests of cutting inspection costs. A less square-shouldered curve will be the result of smaller sample size. The proper economic balance for products in your own plant is what you should seek.

A Double Sampling Plan. The philosophy of giving a lot a second chance to prove itself is a reasonable matter. Hence many "double sampling" plans have been evolved. (1), (2), (3). One such plan which operates in much the same manner as does the single sampling plan just discussed is determined by the following four numbers:

$$n_1 = 50 \qquad n_2 = 100$$

$$c_1 = 0 \qquad c_2 = 2$$

The meaning of these numbers is that we take 50 ($= n_1$) pieces to start with. If in these we find no bad pieces (c_1 or less) we accept the lot at once. If we find more than 2 ($= c_2$) defectives in the first sample we reject the lot at once. On the other hand if we find 1 or 2 defective in the first sample, we take 100 ($= n_2$) more pieces and inspect these. If the total number of defectives in the two samples together (150 pieces) is still 2 or 1 then we accept, but if it is 3 or more we reject the lot.

Thus a final decision can be made on the first sample for acceptance or rejection, or we may be required to take another

sample. After the second sample, however, a final decision is always made.

By reference to Figure 2 (b) it is easily seen that this double sampling plan operates in just about the same fashion as the single plan. A slight difference is noted on lots of .5% defective. For the double plan the chance of acceptance of such a lot is .97 and hence the producer's risk for .5% defective lots is .03. This is a bit less than the .05 for the single sampling plan. On the other hand for 5% defective lots the chance of acceptance is about .09 or .10. Thus the consumer's risk on 5% lots is a bit less for the double sampling plan than for the single sampling plan. Nevertheless the OC curves as a whole indicate that the two plans give comparable protection at the various levels of lot quality.

Amount of Sampling Inspection. Next let us consider the amount of sampling called for on these two plans. This feature is the other fundamental characteristic of sampling plans, the first being the operating characteristics as discussed in the previous sections. The single plan will require 75 pieces for every lot inspected. On the other hand the double sampling plan will sometimes require only 50 pieces before a decision is reached but will require 150 pieces on other occasions, that is, a varying among of sampling. If lots are very poor or very good the average amount of sampling will be near 50, because then a decision is commonly made on the first sample. This would be a saving of inspection over the single sampling plan. But if quality is intermediate the double plan will average more inspection per lot than the single plan. Figure 3 shows this

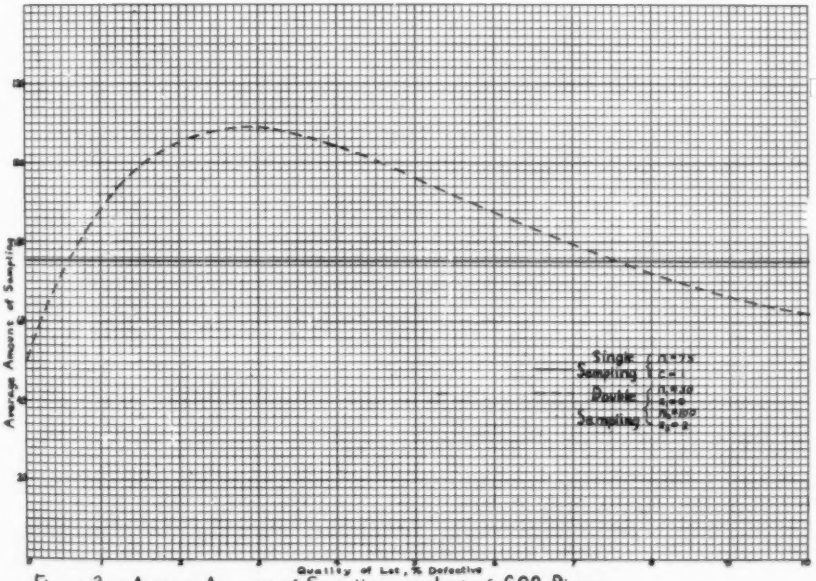

Figure 3 – Average Amount of Sampling per Lot of 600 Pieces

comparison. Thus the double plan requires less sampling on the average for lots of better quality than 1.5% defective or poorer quality than 7.5%, while the single plan requires less sampling on the average between these quality levels. Here is useful information for you on what it is going to cost you to get the protection indicated in Figure 2. There is another angle to this inspection cost, however. It stems from the question: What are you going to do about rejected lots? If all such lots are "detailed", that is, all pieces in the lot are inspected, then the total inspection cost will be made up of the sampling, plus the detailing of rejected lots. If you do this detailing at your own plant it will be a direct cost, while if the rejected lots are returned to the producer who details them, the cost will be reflected in higher prices. Hence a study of the total inspection cost for different lot qualities is important. Figure 4 shows the two curves for total inspection. At excellent quality the amount of inspection is very little more than

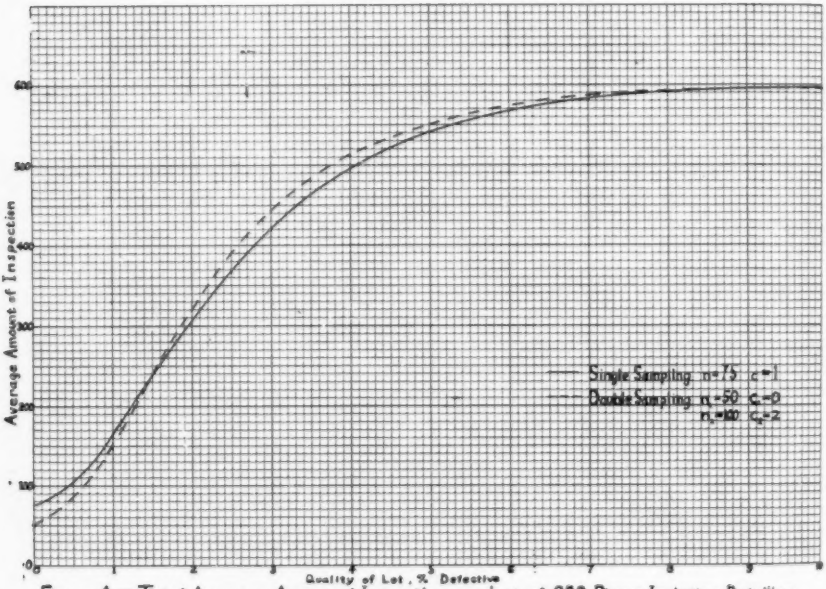

Figure 4 — Total Average Amount of Inspection per Lot of 600 Pieces, Including Detailing

50 and 75 for the respective plans, since almost always the lot is accepted on the first or the single sample. The two curves rise, however, and as the lot quality gets to about 8% defective the average total amount of inspection is practically the lot size, since nearly every lot is detailed. The two curves show that the two plans are quite comparable. The economic plan for you is that one having the proper balance between the total cost of inspection of the kind of lots likely to be sent you and the total cost attributable to the rejected pieces in the lots which can be expected to get by.

Keep Records on Suppliers. As past evidence accumulates on each producer you may want to take one of two courses of action. A control chart should be kept on the results of the single sample or the first sample in double sampling. If a producer stays in control at a satisfactory level of quality, then we can safely increase the consumer's risk at the marginally poor quality, in the interests of decreasing the amount of inspection required. If there is a very small chance that a given producer will send me a lot 5% defective, then I should not mind taking a .25, or .35 or even .50 risk of accepting such a lot, if he should happen to send me one. If his quality level has become much worse it will soon be caught. Thus we can safely cut inspection costs on the reliable producers. On the other hand if a producer has a bad quality level, and especially if he is erratic, showing the presence of many assignable causes in his process, then we may wish to take even less risks of acceptance of a poor quality lot. Hence we will tighten the consumer's risk even though this will cost more inspection. The gain in having fewer bad pieces on which we work will be worth the extra inspection cost.

Basis of Plans - Random Samples. The operation of sampling plans on material of various quality levels and the attendant inspection cost are calculated by the use of laws of probability. These laws assume a random choice of pieces for inclusion in the sample. In practice, if the material has been produced under conditions of strict statistical control, it will not matter much how you go about choosing samples. Since you almost never can be sure of such control in a submitted lot you must therefore take care to try to choose a random sample from the lot. There simply is no mathematical technique for telling you to reject a bushel of "apples" if the top two layers are beautiful red winesaps and the remainder are frozen potatoes, if you examine the top layer only!

Other Possibilities. Up to this point we have been concerned with attributes only, that is, a piece is judged good or bad and that is all. Quality and usability of a lot often depends upon measurements too. Efficient sampling plans based upon measurements can also be figured out, following the same general principles as for attributes. It is still true that you can have as discriminating a plan as you wish, provided you are willing to pay for it.

Another variation to the sampling inspection is to take more than two samples. We might, for example, take one piece at a time and after inspecting decide to:

(a) reject the lot, or
(b) accept the lot, or
(c) take another piece, and check again.

Such a plan is called a sequential sampling plan. It has certain advantages and disadvantages just as single and double sampling have.

Sampling - A B C. To use sampling you must be willing to accept some risks. Know what these risks are and control them at the most economic level for your own acceptance problems.

BEAD EXPERIMENTS TO ILLUSTRATE SAMPLING INSPECTION TABLES

An excellent way to get acquainted with the operation of standard scientific sampling plans is to make some sampling experiments with a box of colored beads and a scoop into which have been drilled a specified number of holes of a suitable size for picking up random samples of beads from the box. The Walco Bead Company, 37 West 37th Street, New York, N.Y., makes wooden beads in various colors which are 10mm in diameter and which serve very nicely for these experiments. The scoop may be made of wood, and generally contains 5 rows of 10 holes each. Holes 7/16" in diameter and 13/32" deep work very well with these beads.

We shall describe two bead experiments which will illustrate certain features of the Dodge-Romig (D-R) Tables. You can modify these experiments to suit your own interests, or to work with Army Ordnance or Navy Inspection tables.

Experiment No. 1. The object of this experiment is to see how a D-R Single Sampling Lot Tolerance Table works. These tables are designed to give the consumer protection against accepting material worse than a specified lot tolerance percent defective (LTPD). Suppose that we want to be protected against accepting material worse than 10% defective. All the D-R lot tolerance tables provide a consumer's risk of 10%; so if our lot tolerance is 10%, then by using the appropriate D-R plan, we run about a 1 in 10 risk of having our sampling inspection pass a lot that is 10% defective. If the lot is of poorer quality than this the chance of its being passed is less. Suppose further that the material inspected comes to us in lots of 750 pieces each from a process controlled at 3.6% defective.

In the D-R Tables, p.73, Table SL-10, column 3.01-4.00, and row 601-800 we find the appropriate single sampling plan n = 100, c = 6. This directs us to take a random sample of 100 pieces from each lot and inspect this sample. If it contains 6 or less defectives, we accept the lot; if it contains 7 or more, we reject or otherwise dispose of the lot. The AOQL column in this table gives a figure of 3.3 on the row we are using. This means that if every rejected lot is screened, cleared of defectives, and re-submitted with all defectives replaced by good pieces, then the plan we are using will pass into production material that, in the long run, averages no worse than 3.3% defective no matter what may be the average quality of the lots originally submitted for acceptance.

Let a white bead represent a good piece and a red bead a defective. Thoroughly mix 723 white and 27 red beads in a box and draw 20 successive samples of 100 beads each. If the scoop is a 50-hole scoop, do not replace the first 50 drawn before getting the second 50 in each sample of 100, but do replace each sample of 100 before starting to take the next sample of 100. This simulates the inspection by single sampling of 20 successive lots submitted for acceptance. Keep an inspection record with the following heading, putting a check mark in column A for each lot accepted, and a check

mark in column R for each lot rejected.

Sample Size: n = 100 ; Acceptance No.: c = 6.

No. Defectives Observed = d ; LTPD = p_t = 10%. AOQL = 3.3%

Lot No.	d	A	R	Lot No.	d	A	R	Lot. No.	d	A	R
1	4	✓		11	7		✓				

Keep an np chart based on the standards np' = 3.6, UCL_{np} = 9.2. If the beads are well mixed, so that sampling approximates true randomness, you can expect to get an observed average, $n\bar{p}$, somewhere between 2.4 and 4.8 which are 3-sigma limits for the standard value np' = 3.6 based on 20 samples.

Now extend the above table so as to include a total of 120 submitted lots. Take the additional 100 samples (100 beads per sample) according to the schedule below which shows one way to alter the bead ratio to simulate incoming lots of progressively poorer quality. The column "Range of Acceptances" shows limits within which the number of lots accepted in a series of 20 lots can be expected to vary. Thus, when this sampling plan is used on a single series of 20 incoming lots, each of which is 7.6% defective, the plan may be expected to accept as few as one, or as many as 14, of these lots.

Incoming Lot Quality p (%)	No. of Beads		No. of Samples taken at this level	Range of Acceptances
	W	R		
3.6	723	27	20	16 - 20
5.6	708	42	20	7 - 19
7.6	693	57	20	1 - 14
8.8	684	66	20	0 - 11
9.6	678	72	20	0 - 8
10.5	671	79	20	0 - 6

Discontinue the control chart record after sample points begin to fall consistently outside the UCL_{np} established by the standards set for the first 20 samples. Notice how the chart provides graphical evidence of deterioration in vendor quality, and how the sampling plan gives increasing protection against accepting too much of such material. The OC curve for this plan would show the proportion of lots that could be expected to get by our inspection, in the long run, at each incoming quality level, but we shall omit the details of constructing this curve. A good reference from which you can learn how to make the OC curve for this plan will be found in Ref. 4, p. 346.

When the experiment has been completed, check the number of accepted lots at each level against the range of acceptances limits for that level to see if your sampling technique has been operated in control. Also, count up the number of defectives in the uninspected portions of all accepted lots. Thus, for example, when p' = 5.6%,

there were 42 defectives in every lot accepted, but we found and removed some of these by inspection, replacing them (in theory) by good pieces. Hence, at this level (p' = 5.6%).

$$\left\{\begin{array}{l}\text{Total no. defectives passed}\\ \text{into stock for this series}\\ \text{of 20 lots}\end{array}\right\} = (42)\left\{\begin{array}{l}\text{No. of}\\ \text{lots}\\ \text{Accptd}\end{array}\right\} - \left\{\begin{array}{l}\text{Total no. defcts.}\\ \text{found \& removed}\\ \text{from these accptd}\\ \text{lots.}\end{array}\right\}$$

When the grand total of defectives accepted has been obtained for all 120 lots received, divide this total by 90,000 i.e., (750) (120). The result should be a figure not greater than 3.3%

It must be understood that AOQL = 3.3% is a mathematical idealization which can only be approximated in the long run by actual observed sampling results. Also, an AOQL figure depends on the assumption that all defectives found in accepted lots, and all defectives in rejected lots, are removed and replaced by good pieces. That is why our divisor was 90,000 in this experiment - we ultimately accepted 90,000 pieces. As a matter of fact, failure to conform in practice with the assumption of replacement of defective pieces does not significantly change the AOQL figure for lots of moderately defective material, but the assumption that all rejected lots are effectively screened and cleared of defectives is vital and must be met (at least approximately) in practice if any valid estimate of AOQL is to be associated with this sampling plan.

Note also that the primary objective of this plan was to secure lot quality protection - the AOQL was just a convenient by-product of the plan, but it was automatically available to us if we could arrange to fulfill the screening and replacement requirements on which AOQL rests. In practice, of course, we would never know how many defectives remained in the uninspected portions of accepted lots, so we could not make the calculation for AOQL that we were able to make in this experiment - we would have to trust the table for this, and figure that in the long run we could expect the material passed into stock to average no worse than 3.3% defective if we continued to fulfill the screening and replacement requirements. We should also realize that this 3.3% is the maximum, and that probably our average incoming quality is considerably better.

Likewise, in practice, a series of 20 submitted lots would not come in for acceptance with each lot at exactly a fixed quality level as was true in our experiment, nor would it be likely that the quality level would shift as uniformly from one series of 20 lots to the next as we were able to arrange it in the experiment. Finally, unless we had reliable inspection records on the past history of a vendor, we could not begin keeping a control chart based on standard values - the chart would be kept on the basis of observed data. (Keeping a control chart as part of the inspection procedure provides a valuable graphical check on both the vendor's quality history and the randomness with which the sampling inspection is performed.) Nevertheless, the experiment is not to be regarded as purely artificial - it faithfully illustrates how the plan can be counted on to give the spec-

ified, over all lot quality protection and AOQL in practice if properly administered.

Experiment No. 2. The object of this experiment is to see how a D-R, double sampling, AOQL table operates. One chooses an AOQL table for the primary purpose of establishing an average outgoing quality limit such that if the correct inspection procedure is maintained, material passed by these inspections will not average poorer than the AOQL figure chosen. Thus, these tables have been found particularly appropriate for within-plant process inspections of piece-parts, sub-assemblies, and final inspections of finished product manufactured on a quantity basis. Lot quality protection is only incidental here - what is wanted is protection against passing to the next department material that is of average quality poorer than the AOQL figure.

Suppose we choose an AOQL of 4%, and that we want to do double sampling of material that comes to us in lots ranging from 601 to 800 pieces. Suppose that the process from which the material comes is expected to be in control at a level between 3.21 and 4%. With these conditions agreed on, we turn to Table DA-4 on p.98 of the D-R Tables, locate the 3.21-4.00 heading in this table, and go down to row 601-800 where we find the double sampling plan $n_1 = 55$, $c_1 = 2$, $n_2 = 105$, $c_2 = 11$. This plan directs us to

(1) Take a random sample of 55 pieces and inspect them. If we find 2 or less defectives, we accept the lot. If we find 12 or more defectives in this sample of 55, we reject or otherwise dispose of the lot.

(2) If, in the first sample of 55, we find 3,4,5,. . . up to and including 11 defectives, we take a second random sample of 105 pieces and inspect them.

(3) If the total number of defectives found in both the sample of size 55 and that of 105 (a combined total of 160 pieces) is 11 or less, we accept the lot. If the total is 12 or more, we reject or otherwise dispose of the lot.

(4) All defectives found in accepted lots are to be replaced by good pieces, and all rejected lots are to be detailed, cleared of defectives, and re-submitted for acceptance.

To conduct the experiment, thoroughly mix 27 red beads with 723 white beads to give a lot of 750 beads that is 3.6% defective. Make an inspection record sheet with the following heading.

Samples: $n_1 = 55$; $n_2 = 105$; $n_1 + n_2 = 160$

Accept. Nos.: $c_1 = 2$; $c_2 = 11$; $c_2 = 11$

Defectives in first sample = d_1 AOQL = 4.0%

Defectives in second sample = d_2 LTPD = 10.8%

Defectives in combined sample = $d_1 + d_2$

Lot No.	d_1	d_2	$d_1 + d_2$	A	R	Remarks
1	1			✓		
2	13				✓	
3	4	5	9	✓		
4	6	7	13		✓	

(The first four rows have been filled in with data to show the four possible ways an inspection of a lot can turn out.)

Keep an np chart on first samples only based on the standards $np' = 2$, $UCL_{np} = 6.1$. If the sampling is random, you can expect to get an observed average, $n\bar{p}$, somewhere between one and 2.9. If the scoop contains 50 holes, you will have to choose one column of 5 holes as the column to be inspected for the extra 5 beads in both the first and second samples ($n_1 = 55$, $n_2 = 105$). Whenever a second sample must be taken, do not return to the box any beads already inspected before getting the next scoopful, but after inspection of each lot is completed, return to the box all beads inspected before starting the inspection of the next lot.

Now extend the inspection record sheet as in Experiment No. 1, and alter the bead ratios as described for that experiment. Continue taking samples and recording results. You will soon discover that you are taking a good many second samples to reach a decision. This means that you are doing more inspection than you had to do in the first experiment.

One practical reason for doing double sampling is that for material of acceptable quality (3.21 to 4% in our case) or better most lots can be accepted with less inspection than is required by single sampling. Likewise, for material of exceptionally poor quality, double sampling will give a decision to reject with less inspection than is required by single sampling. You can test this latter assertion by mixing 600 white and 150 red beads and using the present double sampling plan on this 20% defective material. You should not accept any of these lots in a series of 20 such lots, and most of them should be rejected on the evidence of the first sample.

In practice, it would be foolish and costly to continue using this double sampling plan all the way through to the level $p' = 10.5\%$ as we have suggested for this experiment. A control chart record on

first samples will indicate clearly when incoming quality begins to move away from a level where this plan is economical. When this happens, the best action to take (where sampling is on within-plant material) concerns corrective action on the process responsible for the poor quality rather than on the sampling plan. However, until corrective action begins to take effect, it would be more economical to shift to the SA-4 table, p.86, column 3.21-4.00, and row 601-800 where one finds the single sampling plan n = 60, c = 4. This would give the same outgoing quality assurance with a saving of inspection until the process can re-qualify for double sampling.

To complete Experiment No. 2 after all 120 lots have been sampled, count up the defectives remaining in the uninspected portions of all accepted lots and divide this total by 90,000. No matter how excessive the inspection, or how many lots have been accepted by the experiment, it will be found that the ratio just described will not be greater than 4%. This AOQL figure depends, of course, on the enforcement of condition (4) in the layout of the sampling plan, and is the target at which the plan is aimed. However, the D-R Table DA-4 we have been using gives a LTPD of p_t = 10.8% as a by-product of the plan. None of the lots used in this experiment were worse than p' = 10.5%, so, of course, we accepted none as poor as 10.8%. If you want to check the operation of this plan with respect to this feature, take 20 samples from a lot containing 660 white and 90 red beads. This is a 12% defective lot. Nearly every lot will have to be double-sampled, and not more than 2, if that many, should get by without 100% detailing.

The D-R Tables also provide AOQL single sampling plans and lot tolerance double sampling plans. In all D-R Tables the sample sizes and acceptance numbers have been mathematically determined so that for submitted lots within the process average quality range that locates the plan, the over all amount of inspection including detailing of rejected lots, is minimized. The two experiments outlined here have not been constructed to emphasize this feature, but rather to show how a given plan operates in the face of submitted lots whose quality steadily deteriorates. In practice, corrective action by the vendor, or on the process, is the proper action called for by such evidence. Of course, if a vendor, or a process, shifts and appears to stabilize at a better quality level than that on which a given plan is based, then the proper procedure would be a change to the D-R plan that matches this improvement. A control chart kept in conjunction with the sampling is the best barometer for checking these inevitable shifts in quality level.

References

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USING THE QUALITY CONTROL CHART TO IDENTIFY ASSIGNABLE CAUSES

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In its conventional use in process quality control the Shewhart quality control chart is considered to be a highly effective means for detecting the existence of assignable causes of variation in product quality. It is a device that is often described by saying that it tells you when to act, when to do something to the process to bring it back in line. The point the so called "practical man" often makes is that while that is fine as far as it goes, what he wants to know is the identity of the assignable cause that needs to be controlled or eliminated. While engineering knowledge and special investigation are generally necessary for this final step, judicious use of the quality control chart can often be of considerable help in locating the assignable cause.

Before developing the specific subject with which we are here concerned, let us first briefly review two of the fundamental aspects of the quality control chart as used in process control. First, most industrial processes involve a complex mixture of chance and assignable causes, so complex that a highly precise determination of the distribution pattern of the chance causes is economically impossible or operationally impractical. For this reason it will generally be wise to avoid the use of measurement control charts which plot the results of single observations, although it is realized that in special cases such charts may be very useful. Control charts of groups of four or more will be desirable since they obviate some of the difficulties involved in definitely non-normal distributions, even though they are less precise in pinning down the exact time when lack of control becomes apparent. The estimate of inherent variability should, of course, be based on small groups of observations in order to eliminate as far as possible the effect of assignable causes on the estimate.

Secondly, the quality control chart does not necessarily tell us the exact time when a shift in process level or variability occurred. A small shift in level or variability may continue for some time before being detected since such shifts only slightly increase the probability of a point falling outside control limits. Fortunately, the smaller the shift the less important it is likely to be. In addition, unless all items are tested and results plotted, shifts may originate between samples. It must be remembered that a point outside limits is a much better basis for assuming that an assignable cause has entered the process than a point inside limits is for assuming that no assignable causes have developed.

In spite of the foregoing limitations, the quality control chart continues to be a highly effective means of detecting the development of assignable causes. Let us now consider how the chart can be used to even greater advantage for the purpose of tracking down specific assignable causes.

The beginner is usually cautioned to avoid making too many control charts at first in view of the dissipation of effort and effectiveness.

One or two charts on the most troublesome quality charteristics is a common recommendation. When some familiarity with the use and operation of the control chart has been gained, an attempt to use it to help identify assignable causes may be in order.

Regardless of how complex a process may be, it can be broken down into four general sources of product quality variation: raw materials, machines, men, and methods. If the assignable cause or causes can be pinned down to one of these areas, considerable progress has been made toward the final identification. If two or more sources of a raw material are used, separate charts may be kept on each source. Similarly, separate charts may be kept on different machines (all presumably operating alike), different operators or turns, or on different methods of processing. In addition, the length of time required for an obvious shift in quality level may be a clue to the nature of the assignable cause involved.

In the following illustration (and in all others in this paper), the original data have been modified so that only the general nature of the situation is reflected. Four glass melting furnaces were involved in the general problem of cordiness (defects in glass). Control charts were kept on samples of the product from each of the furnaces. Samples were taken at approximately the same time from each furnace. The results are shown in Figure 1.

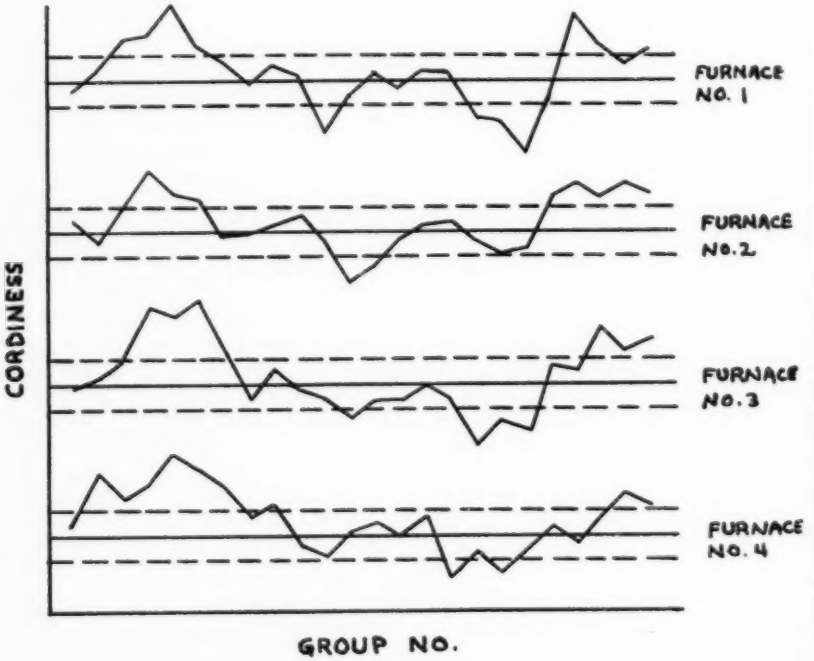

FIG. 1

It is immediately apparent that the shifts in quality level tend to be of the same nature in all of the furnaces. This indicates that the assignable cause(s) is some factor in common to all the furnaces. Factors such as differences in the individual furnaces, and furnace crews, are immediately eliminated from consideration. Our attention is narrowed down to factors common to the four furnaces. In this case the raw materials are all fed into the furnaces from the same bin, hence it would appear that the quality variations in the final product are primarily due to variations in the raw material. In any event, a careful study of the quality of the raw materials would be desirable. It offers much promise for fruitful investigation.

In the next illustration, it was suspected that either the crew or the shift was responsible for the trouble that was occurring. Too many defectives were getting by the visual inspection. The crews were rotated each week and charts prepared as indicated in Figure 2. It was immediately apparent that the source of the trouble was the daylight shift and that the crews were all doing about the same sort of job. Special lighting had been provided for the night shifts. In the daytime, this was supplemented with considerable natural light. It was suspected that the daylight was interfering with the effectiveness of the inspection operation. The windows were painted black so that only special artificial light was used for the inspection operation. The trouble that had been occurring on the daylight shift immediately cleared up.

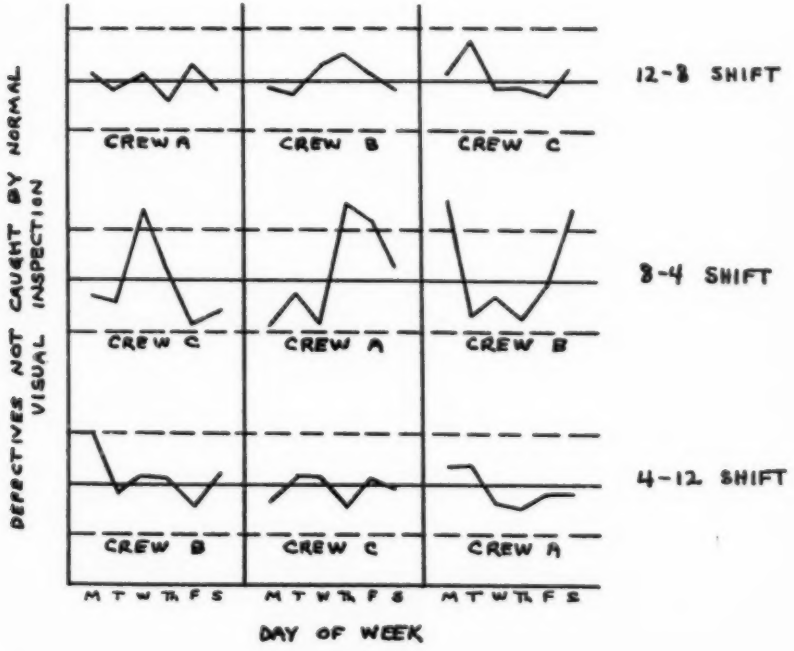

FIG. 2

In another illustration, tool marks were found which were cause for rejection. The analysis in this case was so simple and the result so obvious that control charts were not needed; however, the method of attack was in line with the sort of thing we are considering here and hence is appropriate.

The parts were made on a drum type machine having four cutters and six positions. The part had four trunnions. The trunnions on each of 125 pieces were identified and processed. Thirty-three of the 500 trunnions were found to be defective. The following table indicated the location of the trouble:

	Cutter No.				
Drum Position	1	2	3	4	Totals
A	0	0	3	1	4
B	1	0	2	0	3
C	1	0	4	0	5
D	0	2	5	1	8
E	0	2	4	0	6
F	0	0	5	2	7
Totals	2	4	23	4	33

It was found that the piece was not being properly centered at Cutter No. 3.

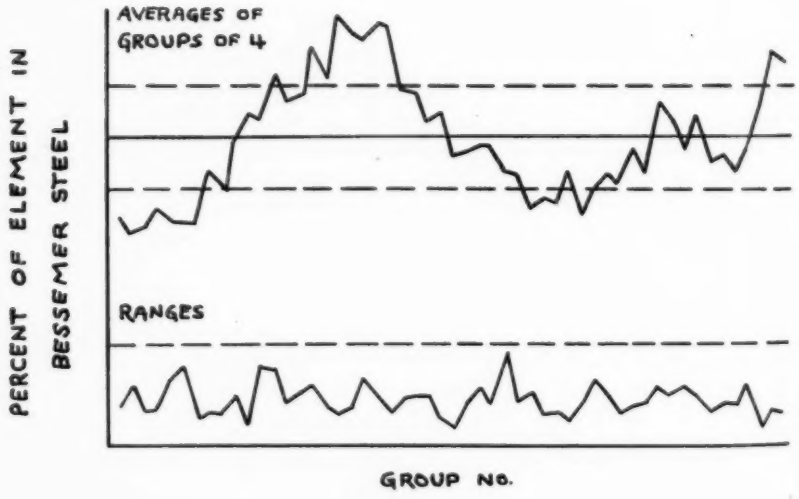

FIG. 3

In this instance, judicious selection of data and a special inspection trial run solved the problem. The importance of proper identification of parts and steps in the process is clearly indicated.

In the last illustration, the time element was of considerable importance. It involved the chemical analysis of Bessemer Steel for one of the elements in it. An analysis was made on a sample of steel from each blow and the results grouped by four's. The chart shown in Figure 3 covered a period of about two months.

While the ranges show nice control, it is obvious that the process level is gradually shifting up and down, about one to three weeks being required for an up or down cycle. Since there are many potential assignable causes that vary from a few seconds to many days in the length of time they require to produce a detectable quality variation in the product, the information Figure 3 gives is particularly helpful. All factors that would cause an up and down shift in quality level in a few hours or less can be eliminated from investigation and effort concentrated on the longer interval factors.

THE USE OF MODIFIED LIMITS IN PROCESS QUALITY CONTROL

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Just as a uniform and uninterrupted flow of materials-in-process may be thought of as the life blood of an organization, so may the systematic control of quality of those same materials-in-process be considered as the tonic which prevents the hardening of industrial arteries, thereby prolonging the usefulness and the life of an organization with a minimum of expense and time out for production sickness. Although there may be other methods of achieving this desirable result, one which has been tried and proved is the application of statistical quality control techniques, developed and perfected for control of the quality of a manufactured product during production, and known as the control chart method. The principles of application of the control chart method have been described elsewhere many times, and need not be reviewed here.

The use of the word "statistical" throughout this discussion may have a different connotation from that which might be attributed to it by a pure statistician, because our approach to the problem is one that would be taken by most practical quality control men rather than by those who are interested in the application of statistical techniques based on theoretical considerations only. In other words, it is necessary for the practical quality control engineer to give due consideration to the many factors which tend to influence the economic side of the picture as well as to the technical factors that must be considered in applying approved mathematical procedures to practical industrial problems. Stated briefly, as much consideration must be given to those factors that determine the cost of quality as to those factors that determine the benefits to be derived from quality.

It is the duty and the responsibility of the quality control engineer to determine to the best of his ability that point on the relative scale of quality where added improvements in the process begin to yield less in return economically than the increase in cost required to produce those same refinements. This idea is portrayed graphically in Figure 1.

Although no attempt has been made toward exactness, it is indicated in Figure 1 that as relative quality moves from a minimum toward a maximum the cost of quality rises slowly at first and then more sharply as quality approaches perfection, whereas the benefits of quality rise sharply at first and then taper off gradually as a state of perfection is approached. The point where these two curves cross may be considered as an optimum value on the scale of relative quality; it is a point which should be approached as closely as possible in any undertaking. If one could determine this optimum point exactly and schedule operations accordingly, then every cent that was expended in improvement of materials, processes, equipment, and so on, would be returned in the form of reduced scrap, rework, and other non-essential manu-

facturing costs, increased customer satifaction, and improved competetive quality. Hence, a minimum cost of operation and a maximum of customer satisfaction result in an economic balance most satisfactory to all concerned.

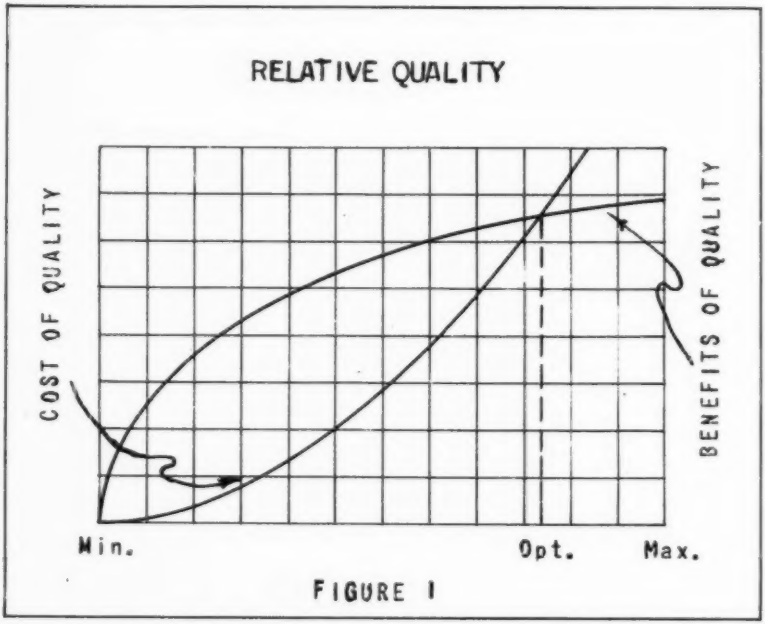

FIGURE 1

Although it follows directly as a corrolary to the above, too often the fact is not well recognized and appreciated that a primary function of statistical quality control techniques is to determine if a product is conforming to the requirement of a specification which has been based, or should have been based, on field performance data and, if not, to help segregate the disturbing influence or influences that cause too-little or too-great a variation in dispersion, or that cause the average quality level to operate at a too-high or a too-low value. The distinction between too-little and too-great or between too-high and too-low is exceedingly important because, presumably, the meaning of the term "Acceptable Quality" is based upon conformance with an established standard. If a standard has been established properly (and this is important to remember), then quality is unacceptable if it is either inferior or superior to that standard. This may seem paradoxical since one naturally assumes that a product is more desirable if the average quality level is higher than that required. Such an inference might be true, and probably would be logical, were it not for the fact that a product must be produced at a profit, and the profit margin is reduced accordingly each time something is added in the nature of a quality refinement which is not required by the original standards.

If a product is new and no standards have been established, the data obtained from systematic and orderly inspection, and from quality control procedures, should serve well as a basis for determining those standards which can be maintained in the future. If the product is competetive, consideration must be given also to quality levels maintained by others in the business in order to avoid adverse customer reactions. Once these standards have been established, based on one's own inspection and engineering data and after due consideration has been given to all other known factors which may have a bearing on the final standards, it then becomes economically advisable to maintain these standards as closely as possible, deviating as little on the side of quality improvement as in the opposite direction. Such a state of control should be maintained just so long as new requirements or changed conditions fail to appear. When such changes occur, however, (and there will be many instances when they will) it will be a test of the quality control engineer's ability to forsee such developments and to be prepared to meet them when they arise. In effect this is a case of being able to read "the handwriting on the wall" as it were, and the quality control engineer who is able to do this and to point out future trends and developments to his associates will occupy a position close to the top of his chosen profession.

The statement has been made that maintenance of a process average which exceeds specification requirements can be just as serious as allowing a process average to deteriorate so that it does not meet specification requirements. Of course the basis for such a statement was economic, and it is not to be inferred that a process should be degraded which is operating at a quality level better than that required. In fact quite the opposite is true. The only time a condition of this kind should be questioned is when there is real evidence that such a refinement is not required and at the same time the cost is excessive which makes that refinement possible.

In the application of the control chart method, limits used most frequently are those of the 3-sigma variety. These are applicable both to $\bar{X}$ and R charts, to p charts, and to a variety of other charts as well. In the discussion which is to follow all references will be to charts of the $\bar{X}$ and R types. Although it has been shown that 3-sigma limits have distinct advantages when a product is being judged by its dispersion about an average, there are times when it is more economical to consider the dispersion of a process with respect to established limits than to its process average. This is true in a great many cases, a typical example of which is illustrated in Figure 2 on the next page. This chart indicates a process which is well centered, has small variance, and contains all sample points well within specification limits which have been established on the basis of application data. Such a condition is not at all unusual in the field of electron tube manufacture, and is one for which adequate provision must be made.

In this particular instance a point falling outside 3-sigma limits would indicate either an uncontrolled process or an assignable cause of variation resulting from a shift of process average or a change in dispersion.

In view of the width of the 3-sigma control limits as compared with the established specification limits it would not be economical to attempt to locate assignable causes of variation for points just outside the 3-sigma control limits. This is the situation that justifies the use of modified control limits. The problem is to find a set of limits between which a process may vary and yet remain, for all practical purposes, within control as far as the specification limits are concerned. Such a solution has been found in the use of modified control limits which are placed, not at a specified distance from the average, but at a certain distance inside the specification limits, depending upon the dispersion of the process being investigated.

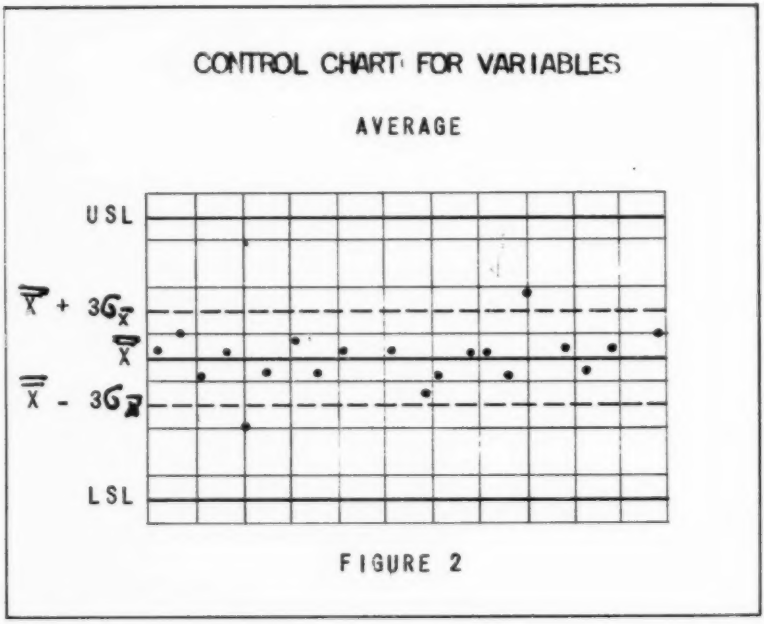

FIGURE 2

Following is a description of the plan which was developed first by the British* and which has been used successfully for a considerable period of time in some of the plants of the company with which the writer is associated. The applicability of this type of limit to the problem at hand is no criterion of its usefulness or of its correctness to the many types of problems one may encounter. This must be determined in each individual instance on the basis of the facts available.

In a normally distributed universe the dispersion of averages of samples of size "n" varies inversely as the square root of the sample size. Thus the dispersion of averages of sample size 4 would be one-half the dispersion of the universe, the dispersion of averages of sample size 9 would be one-third of the universe, and so on. Now if it

* A First Guide to Quality Control for Engineers--British Ministry of Supply, 1945.

is assumed that the dispersion of individual items is equal exactly to the spread between the upper and the lower specification limits, then the dispersion of averages of samples of size "n" will fall within limits which are narrower than the specification limits. If it is assumed also that specification limits have been set at ± S about a rated value, then specification limits for averages of samples of size "n" will become $\pm S/\sqrt{n}$, provided, of course, 3-sigma limits, or limits of similar probability, have been chosen both for the universe distribution and for the distribution of samples.

For example, if specification limits for a certain measurement were 30 lbs. ± 6 lbs, and if the sample size to be used were 9, modified limits for averages would be 18-22 lbs. ($\pm 6/\sqrt{9} = \pm 2$). This means that if the process average were centered, and if individual averages of samples of size 9 were within the limits of 18-22 lbs, essentially no scrap would be produced. In this particular example modified limits actually are control limits, although in most practical applications this does not turn out to be the case. A procedure will be outlined below which can be used in all instances.

If 3-sigma limits, indicating the variability of a process, remain within modified limits, no trouble should be experienced. If, however, 3-sigma limits are wider than modified limits, too great a variability of the process is indicated. When this occurs the process must be improved or consideration must be given to widening the specification limits if application requirement will permit such widening.

The method described above for determining modified limits applies to the special case where a process average is centered exactly within the specification limits. It happens more often than not, however, that the process average is either on the high side or on the low side of center, and that the dispersion is considerably less than could be tolerated were the process average more nearly correct. In such cases modified limits may be determined using the smaller of the two differences between the specification limits and the process average.

In a particular instance, the process average $(\bar{\bar{X}})'$ and the dispersion $(\bar{R})$ are calculated using a number of sub-groups of sample size 5. A preliminary calculation is based upon the results obtained from the first 20 sub-groups. A recalculation is made at the end of the first 40 sub-groups and at the end of every 40 sub-groups thereafter. From this distribution of sub-groups of sample size 5 the distribution is calculated for the universe from which the samples were drawn. As mentioned previously the standard deviation of the universe is equal to the standard deviation of averages of samples of size "n" times the square root of the sample size.

The universe distribution is then placed so that its $A\sigma'$ coincides with the specification limit or limits; that is, the differences between the determined process average $(\bar{\bar{X}})$ and the nearest specification limit is $A\sigma'$. The distribution of the original sub-groups from which the universe distribution was calculated is now placed about this

determined process average and its $B\sigma'_{\bar{X}}$ limit nearest the specification limit is called the modified limit. If the actual distribution of a process follows the normal law (and it does follow it quite closely in a great many instances), then it is quite probable that not more than the prescribed number of defects is being passed in accordance with the desired acceptable quality level (AQL) of the process, provided the averages of the sub-groups remain within modified limits and the range remains within its maximum established limit.

Since it is more convenient to determine a range (difference between the highest and lowest sub-group readings) than to calculate the standard deviation for each sub-group from its individual readings, the value of average range ($\bar{R}$) is used to determine the process standard deviation by means of the factor (d2) which has been calculated mathematically. The standard deviation of the universe (σ') is equal to $\bar{R}/d2$, where $\bar{R}$ is the limiting value of average range and d2 depends upon the size of the sub-group chosen.

Reference to Figure 3 indicates the methods used for calculating the Limiting Range Factor (L) and the Modified Limit Factor (M) for the degree of protection desired both as regards the percent of acceptable defects allowed (AQL) and the degree of certainty of meeting the requirements of the plan chosen. The derivations of the formulae are based on the condition of a centered process average, but are satisfactory also for use with one which is not centered.

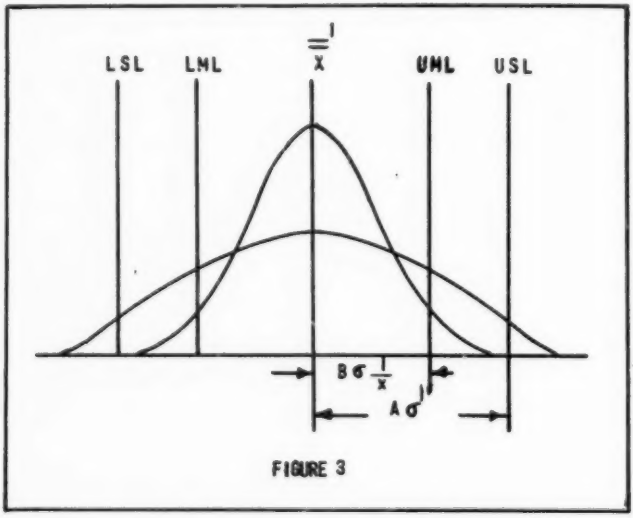

FIGURE 3

If the spread between the process average ($\bar{\bar{X}}'$) and the specification limit is designated by $A\sigma'$, and if it is remembered that the

standard deviation of the universe distribution is $\sigma' = \bar{R}/d2$,

then $(USL - \bar{\bar{X}})' = A\sigma' = A\bar{R}/d2$

and $\bar{R} = (d2/A)(USL - \bar{\bar{X}})' = L(USL - \bar{\bar{X}})'$

where $d2/A$ = Limiting Range Factor L.

If the spread between the process average and the modified limit is designated by $B\sigma'_{\bar{X}}$ and it is remembered that $\sigma'_{\bar{X}} = \sigma'/\sqrt{n}$,

then $UML = USL - (A\sigma' - B\sigma'_{\bar{X}})$

$UML = USL - (A\sigma' - B\sigma'_{\bar{X}}/\sqrt{n})$

$UML = USL - (A\bar{R}/d2 - B\bar{R}/d2\sqrt{n})$

$UML = USL - (1/d2)(A - B/\sqrt{n})\bar{R}$

where $(1/d2)(A - B\sqrt{n})$ = Modified Limit Factor M

Assuming that the possibility of rejection of good lots (Procucer's Risk) has been set at 5% and that a sample size of 5 has been chosen as being most satisfactory, L and M factors are shown in Table 1 for acceptable percentages of defects of 0.27, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 6.0, 8.0, 10, 15 and 20. In calculating L and M factors, the assumption has been made that half of the defects will occur on the low side of the specification and the remaining half on the high side.

AQL-%	L-Factor	M-Factor
0.27	0.775	0.913
0.5	0.828	0.831
1.0	0.902	0.732
1.5	0.957	0.667
2.0	0.998	0.624
3.0	1.07	0.556
4.0	1.14	0.504
5.0	1.19	0.456
6.0	1.24	0.431
8.0	1.33	0.375
10	1.41	0.330
15	1.62	0.242
20	1.82	0.173

TABLE I

After sufficient data have been obtained (usually a minimum of 40 readings of samples of 5), process average $(\bar{\bar{X}})'$ and the average range $(\bar{R})$ values are calculated. The average range is multiplied by the L factor to determine the maximum value which may be used in calculating modified limits. Modified limits for averages are computed by multiplying together the M factor and $\bar{R}$, subtracting the product from the USL and adding it to the LSL. The modified

limit for range is computed by multiplying together $\bar{R}$ and D4 which for samples of 5 equals 2.114.

Although the use of modified limits is quite satisfactory, it should be remembered that there is no substitute for common sense. Whether this method of control is appropriate or whether some other method would serve the purpose better is a matter which must be determined for each particular application.

CONTROL CHART TREATMENT OF PERSONNEL STATISTICS

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Control chart principles, developed by quality control engineers, have in the last few years been found suitable for many types of statistical analyses in other fields. The field of personnel management is especially adaptable to these controls. In fact, the processes of personnel administration can be seen as closely analogous to those of the quality control department though entirely different in subject matter. In the manufacturing process, the quality control department is concerned with identification and reduction of deviations from desired quality and performance of products; the personnel department is similarly concerned with deviations from desired quality and performance of employes. Examples of these might be deviations in amounts of output or efficiency, quality of work, accidents, absences, quits, and similar performances. To carry the analogy further, both the quality control and the personnel departments recommend company policy regarding standards for expected quality and performance, and both are usually staff functions charged with responsibility for the maintenance of these standards. In both cases, failure to maintain these standards results in increased costs of operation. Both departments, in order to reduce deviations from standard, must discover causes for such deviations, and both are charged with recommending or instituting programs for the reduction of off-standard performance. I think also that both departments should evaluate the specific programs instituted to determine their effectiveness in reducing deviations from standard.

Where such a close analogy can be drawn between the functions of personnel and quality control, it is not at all strange that methods used in quality control should be picked up by personnel workers. The one common ground the two functions have is the use of statistics to give direction to their work. It is this common bond that brought quality control men and personnel workers together, and it is through the universal language of statistics that personnel statisticians can perceive the analogy that exists between the two functions.

The personnel department is (or should be) no longer an aggregation of slaphappy extroverts that cannot be held on the payrolls by virtue of competence elsewhere in the plant. 'Today's personnel workers no longer try to soft-soap or entertain workers into tolerance of their daily work in lieu of the more practical incentives of cash, security, and genuine satisfaction. One need not fear being called radical today if he states that these methods do not work. Workers have seen through their flimsiness, and, given more than adaquate backing by our federal government, have banded into hard-fisted businessmen themselves. Management today cannot adopt a take-it-or-else policy in its personnel relations. Management contracts for labor just as it does for materials, except that its choice of suppliers of labor is not free and that the responsibility of the supplier for the product supplied is often found wanting. Even where labor is not supplied by such contracts, it must be treated just the same. Under such conditions, management's ingenuity for increasing labor productivity and reducing labor costs is severly tested.

Parallel to this rise in the status of labor and decline in management's control over the life and will of the working man, has been an increase in the scientific technology of human behavior. Principles of human behavior that were formerly confined to the schoolroom and mental institution began to find their way into everyday life situations. The questions of why people act as they do and how they can be made to act differently became subjects for popular consumption. A few bold industrialists sponsored experiments in human relations in their own plants, and the results supplied the wedge for an invasion of industry by psychologists and psychotechnicians. Old principles that a man's behavior and efficiency were influenced very much by factors largely psychological in nature assumed importance in industrial management. It was recognized that a man responds to incentives which contribute to his pride, his security, his desire for belonging to a group, and his desire for accomplishment, and that his behavior as a worker depends on how well he is supplied with such incentives. Psychologists and biologists saw their age old demonstrations of the wide differences in individuals with respect to abilities and aptitudes begin to attract the attention of modern business managers. Industry started to realize that native qualities of the worker made a difference in his performance.

But it was not only these principles of human behavior that impressed management. The demonstrations of their validity would not have been recognized but through the statistics and methodology used. The classical experimental method and statistical techniques, in modified and simplified form, were used to present the results of industrial investigations. For instance, psychological tests proved their worth in correlation scattergrams showing that efficiency of workers went hand in hand with test scores; eye tests and accident proneness measures were demonstrated as they reduced accident figures or increased efficiency; morale building programs and human relations measures were reflected in measurable reduction in turnover and absenteeism. The value of the personnel technique was demonstrated by making obvious the dollar and cents returns resulting from increased efficiency, reduced turnover and accidents, and other indices. Management began to think in terms of the factors which contributed to labor costs and the tremendous springs of human resources which could be tapped to give greater returns for labor expense. Management began to see that competitive advantage could be gained by discreet development of its human resources as much as through improved business methods, machinery, and product.

As personnel workers, management more and more now selects people especially trained in human relations. It tenders to them its labor problems, and gives them experience in how these labor problems relate to overall company functioning. It elevates the head of the personnel department to membership in the top executive staff and gives him responsibility for establishing and administering sound personnel practices. It supplies him with a staff of technical specialists: wage and salary people determine equitable wage ranges and compensation practices; employment experts study qualities of men and demands of jobs, fitting the two together in making most efficient placements; training sections develop the competence of men on jobs, applying the best principles of education; specialists handle negotiations with employe organizations; and other groups develop recreational, social,

and other programs to build working morale and maintain company allegiance of employes.

How then, do statistics fit into the picture? What part do they play in the personnel programs mentioned? Seemingly, except for perhaps wage and salary work, the people in the personnel department do not deal with figures. Actually, though, they are all shooting for an objective - the greatest return for the labor dollar. Although sometimes seeming to spend most of their effort to dispense with overhead funds, they are actually trying to reduce expenses. Such expenses show up in numerous personnel statistics, or indices. Turnover figures are kept periodically and represent considerable costs. One replacement for the most common factory worker costs between $150 and $200. Rates of turnover may run from one to fifteen per cent per month. Considering the size of some companies, each per cent difference in rate represents a large expense. Accident frequency and severity rates, as well as dispensary visits, express costs. Employee efficiency or productivity figures obviously show value received for wages and are affected by personnel practices. Morale indices, of which there are numerous types, are indications of unrest and possible future costs in reduced efficiency, turnover, or labor trouble. Each grievance or each day in negotiations represents an expense of time and money of some of the company's most highly paid personnel. All these are shown in the appropriate statistics. As figures for the whole plant, they represent indices of the effectiveness of the personnel practices of the plant. As figures for departments, sections, or occupations, they point up sources contributing to ineffective operations. The alert personnel worker watches these indices and aims at their control. When they reflect undesirable conditions of employe relations, he seeks the sources of difficulty and tries to correct them.

If you have been following me up to this point, you have probably just thought, "Ah - that's when control charts come in." Well, that is right.

I have been asked to speak here because we have had a little experience with the use of control charts with personnel statistics. The two illustrations I am going to present represent only a dipping into their possibilities, and should be taken as such. However, I believe, and will show later, that a whole practical system of personnel management control might be built around the intelligent use of these charts.

The first example deals with the problem of a rising turnover rate in a manufacturing plant. In this plant, a monthly turnover report shows the percentage of the total work force which is terminated during a month. Similar reports are kept by several plants of the company and are issued by the Bureau of Labor Statistics in Washington. I mention this because the other reports afford a frame of reference against which the plant judges the significance of changes in its own records. Because the rate of turnover remained relatively high for a number of months, the management decided that an investigation should be made of the causes for turnover during the previous six months. The object would be to correct the causes, if possible.

Traditionally, the method used for such studies is to tabulate from a large number of turnover records the reasons given by the employe for

leaving, and to break down turnover records by job, department, age, sex, and similar groupings. If possible, the major reasons are determined and recommendations, usually of a plant-wide nature, are made for reducing turnover. This method requires months of detailed study and often much investigation into areas of insignificance. This time we decided to conduct the study through the use of control charts, and investigate only areas which were statistically "out of control."

First, separate figures were already kept for hourly and salaried employes, which showed that it was turnover amongst the hourly group that was causing the trouble. The next step was to separate the male and female employes, since the male and female rates differ greatly, and fluctuate independently. At this point, we were satisfied that the female rate was out of line by comparison, being practically double the male rate, which compared favorably with BLS figures. It happens that female labor in this plant is about 70% of the total labor force, so the rate amongst women would be quite important. The plant employed about 2,000 women.

CHART NO. 1a

CONTROL CHART OF TURNOVER BY DEPARTMENTS (6 months)
Salaried Employees

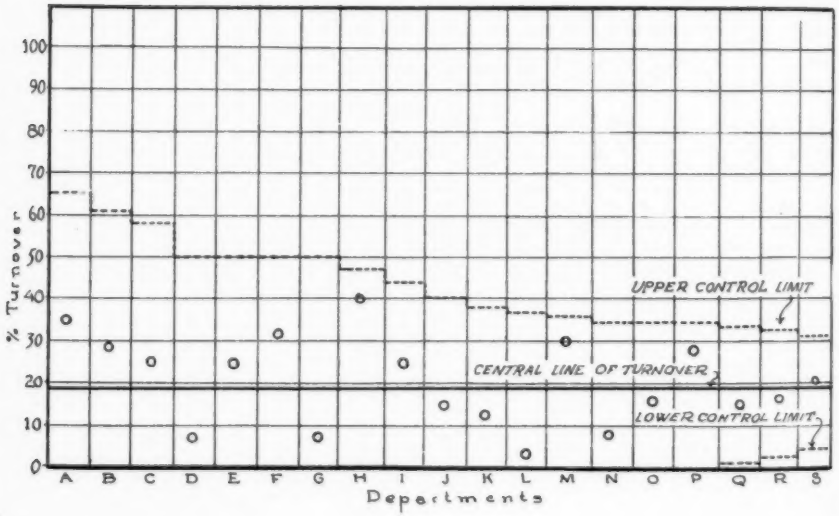


CHART NO. 1b

CONTROL CHART OF TURNOVER BY DEPARTMENTS (6 months)
Hourly Male Employees

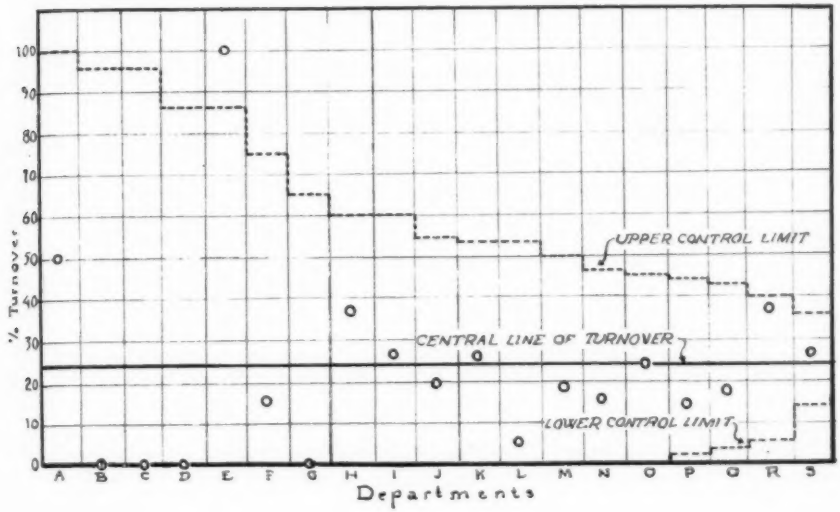
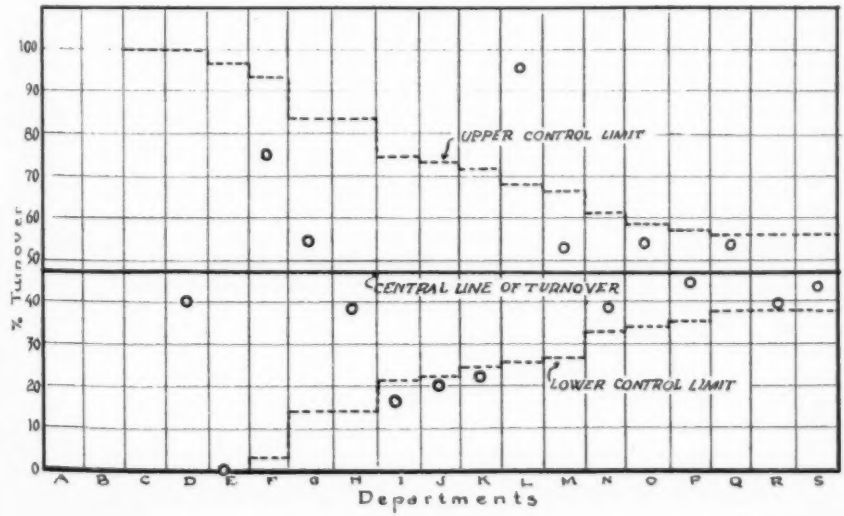


CHART NO. 1c

CONTROL CHART OF TURNOVER BY DEPARTMENTS (6 months)
Hourly Female Employees



The turnover rates were then computed for all departments in the plant, and put on the control charts which you see here (Charts 1 - a, b, and c). Just to play it safe, similar charts were made for hourly female, hourly male, and salaried employes. The reason for including the latter two was that although the total rates for salaried and male hourly employes were not out of line, individual departmental differences may show danger spots. These charts are based on the quality control methods for plotting fraction defective. In this case, the number of employes leaving is analogous to defective inspected parts, and the percent turnover per department is analogous to the fraction defective per sample. The "central line of turnover" is the turnover rate for the whole plant and is analogous to the fraction defective for a total inspected lot over a period of time. The difference here is that inspection samples are usually in a time series, while our samples were all taken at the same time. The control limits are placed at three standard errors of the percentage from the central line. Since the size of the samples differed, the limits are staggered. The departments are placed in order from the smallest to the largest for purposes of presentation.

It is apparent that turnover rates for the salaried and hourly male groups were in control by departments. In only one case (H) for salaried workers, and one (R) for hourly males did the rates reach the upper two sigma limits. On the chart for hourly female workers, we found several interesting things. In the first place, department L was way above what we might expect from a chance fluctuation around the general turnover situation in the plant. Department Q approached the three sigma limit rather closely. These were among the largest departments. On the other hand, departments L, J, K, and E, and R - which was also one of the largest - were around the lower three sigma limits.

Further investigations consisted of an examination of the conditions in each of these departments to uncover causes for the abnormally high and low turnover rates. Physical working conditions were very good throughout the plant and could not seem to be a contributing factor. Likewise, the nature of work being done was similar in some of the contrasting departments. The one outstanding difference seemed to be in the supervisory practices being followed. Both supervisors of departments L and Q were good, honest, hard-headed production men who had taken little notice of the subtle personal element necessary in running a department consisting predominantly of women not used to factory work. The men heading departments J, K, and R had been giving considerable attention to orienting and training the new girls for their work, and lent a personal touch to supervision. Supervisor R in particular, heading a large department, had carefully selected a number of the older and more personable girls as instructors for the others. They gave more attention to seeing that new employes were made to feel at home, were informed about company facilities, and were made acquainted. The supervisor himself expressed the same spirit in his dealings with the workers. It seemed quite probable that this difference in attitude had much to do with the difference in turnover rate.

With this in mind, the turnover control charts were presented to a plant management committee, and in turn to the department heads during conferences on the subject. In a positive manner, the advantages of

the methods used by supervisors J, K, and R were brought out. The other supervisors already harrassed by the problems of high turnover were anxious to start similar programs. Accordingly, with the aid of the training group, more personalized induction and orientation programs were set up and greater attention was given to personalized treatment of employes on the job. The turnover rate was substantially reduced in subsequent months.

The control charts were an excellent basis for presenting the turnover problem to the department heads. The analogy to quality control strikes their fancy. The charts show the problem very graphically, and the limits give them something to shoot at. An open minded attitude that the company is searching for the causes of rates out of control, rather than blaming the supervisors, helps to enlist cooperation and assistance in trying to reduce it.

Another example of the use of quality control charts is in employe merit rating. As you may know, merit rating is a method in which supervisors rate the performance of each employe on various factors of his work - such as quantity of work done, quality of work, dependability, job attitude, knowledge, and others. For each factor, the ratings indicate performance from very bad to exceptionally good, or some such arrangement, and are often converted to numerical scales. The numerical values for each are added to give a measure of the employe's performance. Thus, the rating score may be used to determine increases in wages, promotions, or layoffs of employes or other actions.

One of the biggest difficulties in getting a workable rating plan is the differences in opinions and standards of supervisors who do the rating. For instance, employes working for one supervisor may be called "good" and get a higher rating than those working for another supervisor who judges the same people only "fair." These differences soon become known to employes and create much unrest and complaints. It is a problem of those administering the rating plan to determine when these inequities exist and to overcome them. Most good rating plans include training programs for supervisors to get them to think alike and to avoid bias. Some try to correct for these biases by adding or subtracting quantities to the supervisors' rating according to whether they rate high or low. This system to me is impractical for several statistical and psychological reasons.

Control charts can be used as a means of patrolling ratings submitted by supervisors. They help to detect the most flagrant cases of high and low rating and to give individual attention to supervisors who need it most. Charts 2a and 2b show averages and standard deviations for ratings made by eleven supervisors in one branch of the company. They are based on total ratings of employes working for the supervisors. The control limits are placed at both two and three standard deviations from the grand average and total standard deviation for all supervisors.

CHART NO. 2a

CONTROL CHART FOR RATINGS AVERAGES

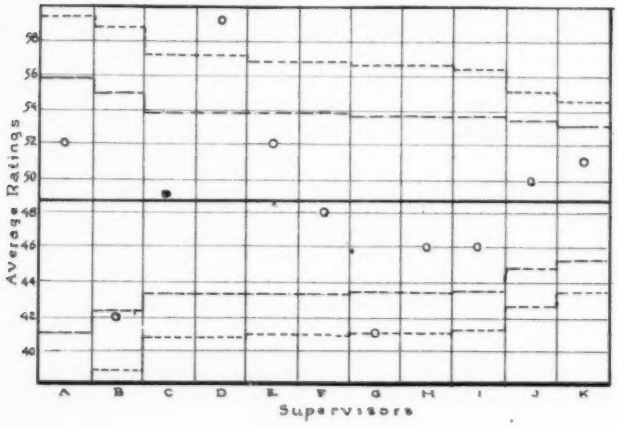


CHART NO.2b

CONTROL CHART FOR RATINGS - STANDARD DEVIATIONS

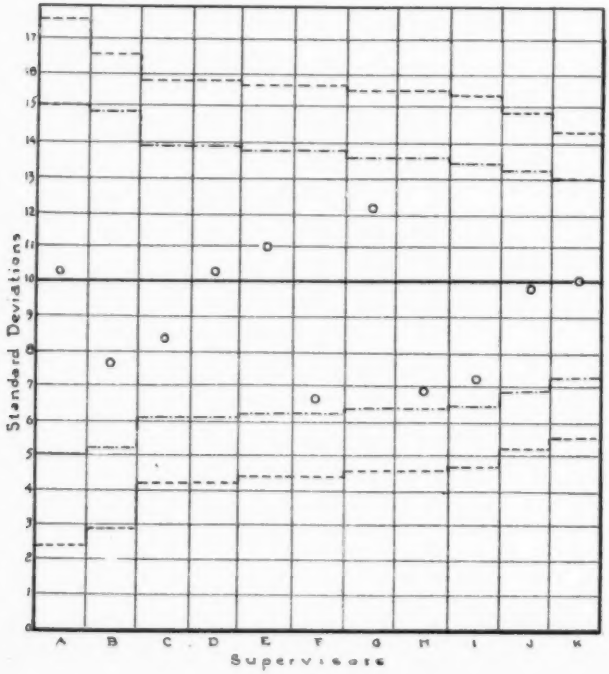


Chart 2a shows that supervisor D was out of control on the high side and supervisors B and G were out of control on the low side. The conclusion would be that some reason other than chance variation around the general level of rating has caused these deviations. It is not fair to assume that the performance of all groups should be the same. Either the people working for these supervisors are actually so much better or worse than those working for others, or the supervisors were using different mental standards in their rating.

As in quality control, our next problem was to contact these supervisors to find out what the assignable causes for the deviations were. In doing this, the rating coordinator discusses with the supervisor just what the job requirements of these men are, and what the facts of their performance have been. Through such discussions it can be determined whether or not their performance has actually been as the definition on the rating chart specified. The coordinator, of course, is familiar with many jobs and performance standards and can help standardize the supervisors' thinking. After such discussions, the high-rating supervisor felt that he had been overestimating the performance of his men, and made re-evaluations. Seeing the control charts did much to impress the men that more careful thinking on their part was desirable. The same thing occurred with supervisor B, who was underrating his people. However, investigation of ratings made by supervisor G showed a different state of affairs. He had rated fifteen people. Of these, two were so poor that their release was being contemplated, and two had been new and had not yet learned the work. As a result, the average of the group was pulled down considerably.

Chart 2b on dispersion has a different application. Proper dispersion of ratings is an important factor also in practical administration of a rating plan. Failure to spread ratings occurs when supervisors do not give sufficient attention to ratings or are not able to understand clearly the different levels of performance of employes. In such cases they tend to rate everybody practically the same. This is bound to result in injustices or failure to bring about proper action to some of those rated. Whereas charts for averages will not show this condition, charts for standard deviations will. In the example shown here, none of the supervisors were out of control. Had there been any, the same type of follow-up action would have been taken as for those out of control on the chart for averages.

The value of control charts for this purpose is that they simplify administration of the rating plan by enabling the coordinator to spot those sources of most obvious difficulty. They also provide an excellent graphic tool for explaining the situation to supervisors.

Similar control chart treatment of other personnel statistics can be used. Mr. Charles Bicking, of Hercules Powder Company, demonstrated to the American Statistical Association its use in connection with statistics of accident rates, production records, overtime hours, and merit rating. Mr. Dwight Stewart of RCA Victor showed members of the Philadelphia Statistical Association that he had applied control charts to job evaluation statistics, using control limits around a linear correlation curve which were based on the standard error of estimate. We have experimented with control charts for absence and turnover statistics in time series, but have encountered difficulties with sea-

sonal and cyclical trends. In such cases the use of control charts is limited by the amount and nature of data used. It would be a mistake to assume that control chart treatment is possible or practical for all personnel statistics, or that the control chart method is the best way to identify and analyze all personnel problems.

By-passing some of the limitations and difficulties of personnel statistics, which might require attention, let us see how the control chart method can be applied to a more complete program of personnel administration. The function of personnel administration, as previously outlined, is three-fold: to establish reasonable standards of quality and performance of employes, which affect operating costs; to detect undesirable deviations from these standards; and to reduce such deviations through appropriate personnel programs.

Measures of the quality and performance of employes can be shown by a number of statistical indices, of which some of the more important are: productivity or efficiency records; absence and turnover figures; accident frequency and severity rates; and employe morale indices. Numerous secondary indices can also be identified. For instance, merit ratings and quality records provide secondary indices affecting productivity, as do records of learning time for new employes. Again, it must be remembered that measures of productivity for different groups may take different forms - various sales performance records for salesmen, amount of output and per unit cost for supervisors, simple output records for assembly workers, etc. The number of grievances provides a morale index. Breakdowns by quits and discharges are secondary turnover indices.

The major indices mentioned above provide statistical bases by which the personnel department may guide its work. Historical statistical records of each can be used to establish reasonable standards in objective terms.

Visualize, if you can, a set of master control charts showing these major indices for a company. They include statistically established control limits of chance fluctuation, and can be broken down by department or supervisor. Statistics are gathered and posted to the charts monthly, perhaps, giving successive time samples. When significant deviations occur from the expected trend, they become signals for investigation to locate the assignable causes. At this time other charts could be set up for localizing the cause by department or by other sub-factors which may have contributed to the change. It may be, of course, that an index out of control may be so from reasons not attributed to personnel management - for instance, a labor shortage, a lack of materials, or a change in operations. In these cases, if we are satisfied that they are the assignable causes, no action may be necessary. Where the assignable cause can be corrected by proper personnel action, a program could be undertaken to fit the situation. The effectiveness of the program is shown by its tendency to bring the index back in control. The turnover application of control charts, which was presented earlier, can now be seen as a follow-through which would occur when the master turnover index got out of control. Numerous other examples could be given of possible applications of control charts to track down assignable causes when these major indices get out of control.

Such a system of control, accompanied by an appropriate program for gathering the necessary data, would seem to form a basis for real scientific personnel administration. Whether or not the scattered successful applications of control chart treatment could be practically extended to a program this comprehensive, remains to be seen.

QUALITY CONTROL OF SUB-ASSEMBLIES

H. R. Bolton
Harrison Radiator Division - General Motors Corporation

Quality control of sub-assembly and assembly operations is a very important item in the Harrison Plant of General Motors. At Harrison, we manufacture various types of heat transfer products. The Buffalo Plant, where I am employed, manufactures car heaters and defrosters for all makes of General Motors Cars and for United Motors Service. The major portion of our operations are in the sub-assemblies and assembly fields. I believe it will be advisable to consider briefly a conception of what the term "Control of Quality" means. This term has been used rather loosely in the past, and the conception of its meaning may be different in various industries or between plants in the same industry. My definition is as follows: "Quality control is essentially the control of variables in the manufacturing process." In any manufacturing operation many variables are encountered. A careful study will show that these variables may be grouped into four main classifications.

1. Raw Materials. Raw materials vary in composition and characteristics. It is a well known fact that some copper ores have a very high percentage of copper while copper ores in another locality may be lower in copper content and contain many additional impurities. It is easily seen that a lot of variability in plants may be attributed to the variable encountered in raw materials.

2. Men. Men vary in skill, job knowledge, and a degree of carelessness. I think this fact is fairly obvious. It is quite possible to go into detail on the effects of this variable in the controlling of processes, but it seems more appropriate here merely to mention it as one variable encountered in any manufacturing operation.

3. Machinery and Equipment. Machinery and equipment are always subject to wear. It seems logical to suppose that we can hold parts to closer tolerances when these parts are produced on a new machine. As this machine wears, it has a tendency to get out of adjustment, and the variability encountered is much greater.

4. Manufacturing Conditions. By manufacturing conditions, I have reference to temperature, humidity, composition of coolants, lubricants, etc. These facts all contribute to variation in the quality of manufacturing operations.

Let us now look at the requisites for a good quality control program. For many years quality control was essentially a separation of good and bad parts. This job was carried on by the inspection department which inspected the product or parts merely to determine if the specifications had been met. This type of quality control can no longer be tolerated.

Industry has made very rapid strides in providing better plants to work in, better equipment to operate, new and different types of material to work with, better methods of distribution, etc. It is now time to develop better methods for controlling quality. Industry is

in a position very similar to that encountered by the railroads. Years ago, when fast express trains traveled 30 and 35 miles an hour, railroad crossings were considered dangerous spots. At that time, the railroad posted signs along the track approximately 1/4 mile from each crossing, notifying the engineer to blow his whistle twice. It was intended that this would provide ample warning to anyone crossing the railroad track.

Then came an era in which rapid strides were made by the railroads to provide better and faster means of transportation. Larger, more comfortable, and faster trains were provided to service the general public. Today, there are trains traveling 85 to 90 miles an hour, but occasionally one still sees these signs, "Blow whistle twice" along the railroad tracks. Some of these signs are still 1/4 mile from the crossing. The engineer now blows once to let you know he is coming and then again a second time to let you know what he has done.

We, in industry, cannot afford to place ourselves in the same position because we do not have an efficient quality control department. So in addition to separating good and bad parts, we must take other factors into consideration. A good quality control program should investigate and locate the sources of defectives. This must be done to prevent further defects from getting into the line. After locating the sources of defectives, it is the duty of the quality control department to definitely fix responsibility for spoilage. This spoilage may take the form of either scrap or re-work. Once a source of defects has been traced down and the responsibility fixed, it then becomes the responsibility of the quality control department to set up some method of control to prevent a reoccurence of the defect. These then are some of the requisites of a good quality control department. With these few points in mind, we are now ready to discuss quality control of sub-assembly operations.

The first step in looking at the over-all picture of quality control sub-assembly operations is to examine and analyze existing quality standards. Quality standards must be in line with the law of diminishing returns. Simply stated, this means that the higher the quality standards, the greater will be the cost of manufacturing. This is illustrated in Figure 1. From this chart it is clear that as we reduce the working tolerance of a sub-assembly, the cost will rise sharply. In view of this fact it behooves the quality control department to be extremely cautious in setting up quality standards. Insisting on too high a quality may cause the company to throw thousands of dollars out the window each year.

If you are manufacturing a product that has an expected life of five years, and you try to build a product that will last fifty years, your costs will skyrocket. It is very important that quality standards once established, be thoroughly understood by product engineering, production supervision and employees, and also by inspection supervision and employees. Unless these groups thoroughly understand the quality that is required, we cannot hope to economically produce units to these quality standards. Many of the discussions in the

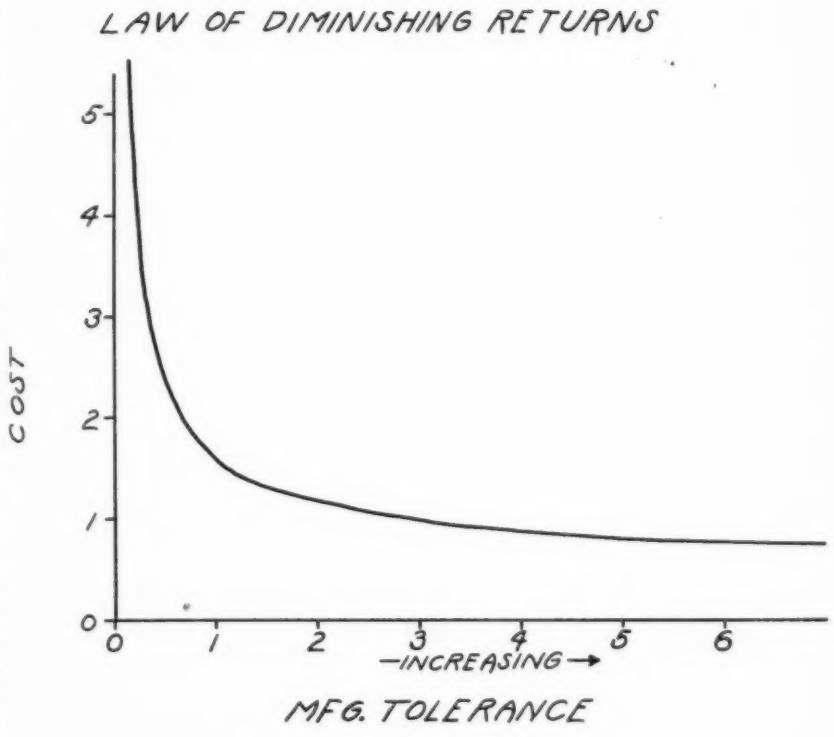


Figure 1

shop regarding quality matters arise from the fact that these groups do not thoroughly understand or have a clear conception of the required quality standards.

Merely telling an inspector what quality is required of a particular sub-assembly does not assure that he thoroughly understands what is desired. Some method must be developed for determining the efficiency of inspectors. Mr. Juran in his recent book on inspection organization and quality control has given a very fine method of figuring inspector efficiency. Mr. Juran's method is based on three assumptions:

1. That for inspectors, as well as shop operators, it is desirable to determine the percentage of work correctly done.

2. The inspector's job is to correctly inspect the parts submitted to him. Hence, his percent of work correctly done is the percentage of pieces correctly inspected.

3. A percentage of good pieces correctly identified is not a measure of the accuracy of the inspector. For example: We have a lot of 1000 sub-assemblies. In this lot there are 980 good units and 20 defective ones. If the inspector did no work whatsoever on this

lot, this would indicate 98% of his work was correctly done, and this assumption would be absurd.

If we can go along with Mr. Juran's assumptions (which appear to be very logical), then the following method should be used to figure the accuracy of inspectors. Let us call the number of rejections originally in the lot of sub-assemblies "m". The number of defects correctly identified by the inspector we shall call "d". If the work of the inspector is re-checked by a check inspector, the defects missed by the inspector will be found presumably by this check inspector. The number of defects missed by the inspector we shall call "b". Obviously then, $d + b = m$, or the number of defects found by the inspector, plus the number of defects missed by the inspector, will equal the total number of defects originally in the lot. The percentage of defects correctly identified by the inspector will equal $100\ (d/m)\%$ or $100\ d/(d + b)\%$. This is an important relationship, and should be the basis for measuring the accuracy of inspectors.

This method of figuring inspector efficiency works very well in cases where very little individual judgment is required of the inspector. Such cases arise when sub-assemblies or parts are checked by means of "go" and "not go" gauges. In using this method for checking inspector efficiency, three factors must be kept in mind.

1. Do not let the inspector know when his accuracy check is to be made. It is only natural that if the inspector knows before hand that his work is to be checked, he will exert extra effort to be sure his work is accurately done.

2. The same gauges and measuring instruments used by the inspector must be used by the check inspector. This is necessary because we frequently find that there is a variation in accuracy between gauges and/or between measuring instruments.

3. If the inspector's supervisor has instructed him to pass certain types of defects, he should not be penalized. In all cases the re-check inspector must work to the same instructions as the bench inspector.

There are types of inspection, particularly visual inspection, where Mr. Juran's method does not seem practical; for instance, inspection operations where a considerable amount of judgment must be excercised by the inspector. An example of this might be the inspection of a painted surface for dispersion of spatter finish. We have approached this problem as follows.

Samples of acceptable and unacceptable quality are selected and placed on a sample board in the inspector's work area. These samples are thoroughly discussed with the inspector before he is allowed to proceed with his work. Each inspector on the same type of work is required to submit a daily report showing the number of pieces inspected and the number of pieces rejected for each type of defect. Periodically these reports are analyzed to determine the percentage of defects for each type of defect found by the various inspectors. A simple bar graph is drawn showing variation between individual

inspectors. An example of this type of chart is shown in Figure 2. This method does not attempt to measure inspector efficiency, but is

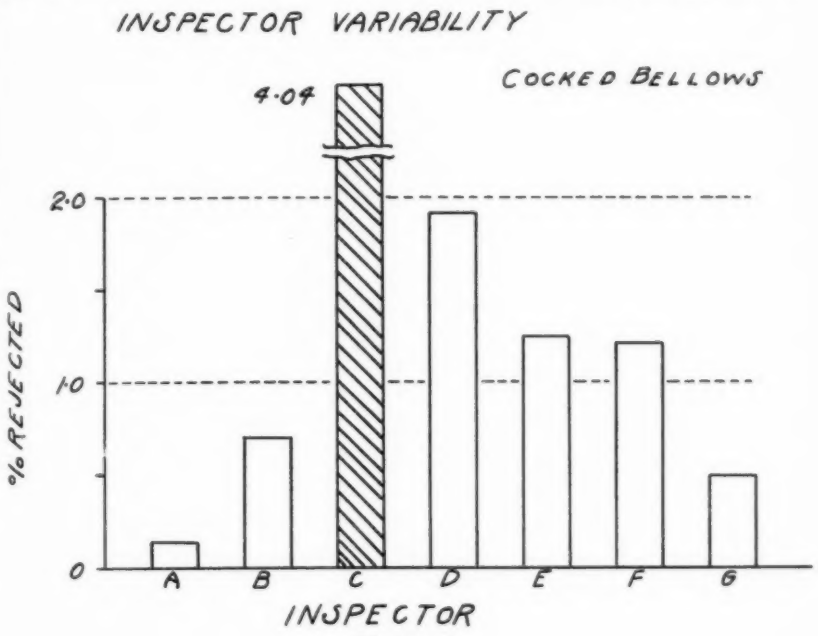


Figure 2

merely used to determine variations between individual inspectors. It is merely a guide post to show us where additional training may be necessary. If an inspector is either exceptionally high or especially low in comparison to the other inspectors, it is a very good indication that he may be "off the beam."

Having determined the efficiency of our inspectors, it is only logical that we make a thorough study of the manufacturing operations and inspection procedures in the area where the statistical quality control program is to be inaugurated. This is a very important step, and should not be eliminated. The manufacturing operations should be thoroughly studied to enable the quality control operator to have a thorough and unbiased picture of each operation. It will be necessary to include a study of sequence of operations, types of machinery and/or equipment used, types of materials used, methods of handling material, method used for handling parts produced, and methods for disposal of scrap and rework. The inspection set up should also be thoroughly analyzed to determine that inspection check points follow the critical operations. An analysis should be made of all existing inspection records to determine if adequate, accurate data are available. In many cases it will be found that inspection data is not reliable because of inspector variability. In this case, new data must be gathered.

Upon completion of the study and analysis of manufacturing operations and inspection procedures, it is necessary to compile the preliminary data that is to be used as a basis for controlling quality. In compiling data, one point should be kept firmly in mind. Inspection record sheets must be so designed that all pertinent data are recorded with a minimum of effort and confusion on the part of the inspectors. This may necessitate a revision of existing inspection record forms.

Upon completion of the gathering of preliminary data, the entire program is to be reduced to writing. This involves drawing up of all necessary control charts based on the preliminary data, the development of the procedure to be followed in the program, and any other information that may be of value in selling the program to supervision. Once a program has been reduced to writing, it should be presented to top management for approval. It is important to secure the approval of top management at the start of the program. Generally, if the program has been reduced to writing and thoroughly presented, top management can readily be sold on the program and will help clear some of the obstacles from its path.

Upon approval of the program by top management, it is desirable to have a preliminary meeting with the heads of the various production and service departments. In our plant this would involve the Chief Design Engineer, Head of Methods and Time Study, Head of Tool Design and Tool Room, Production Superintendent, Maintenance Superintendent, Head Purchasing Agent, Chief Inspector, and Head of Cost Accounting. At this preliminary meeting, the entire program should be thoroughly discussed so that each of these individuals will have a clear conception of how the program will operate and what part their respective departments will play in its operation.

The use of statistical methods of quality control are of little value unless corrective action is taken when points on the control chart fall out of control. The reasons that points fall out of control are many and varied. There is probably no one person who can accurately determine the reasons for an operation or process being out of control. Consequently it is very essential that a corrective action committee be formed. This Corrective Action Committee should be presided over by the statistical quality control engineer. The production foreman in the department, the inspection foreman, a representative of the tool department, methods department representative, and product engineer should form the nucleous of this committee. Other members of management may be called in from time to time as necessity warrants. It shall be the responsibility of this Corrective Action Committee to meet at least once a week to discuss operations that show lack of control. This committee will investigate these operations and determine what action is necessary to bring these operations in control and also to decide when this action shall be taken. Any corrective measures taken will be reported to the committee at subsequent meetings.

As soon as the Corrective Action Committee has been formed and the program explained to them, we are ready to go to work. The control charts are placed in the department. These charts are generally mounted in a central area and are drawn large enough so that they

can be read easily by all employees in the department. These charts may be of the "Fraction Defective" or "Number of Defects" type. The type of charts used will depend upon the product to be controlled. Knowledge of production operations, type of product, volume of production, etc., will determine the type of chart which will be of greatest value in the control work.

Of equal importance with securing top management approval prior to the start of the quality control program is the responsibility to keep top management informed of the progress being made. This can easily be accomplished through the medium of weekly reports. It has been our practice to issue weekly quality reports to members of top management, members of corrective action committees, and shop supervision. This report is broken down into two parts. Figure 3 is a copy of our Vendor Quality Index Report. This is a progress record of the quality of one particular model by weeks. Our quality index value (see Figure 4) is the average number of defects per unit. We use this figure because it is often found that a unit will have more than one defect. Our data are taken from the inspection reports at our final inspection station. When plotting a graph of this kind, we find that the lower the quality index value, the higher the quality of the rejections found at final inspection. We do not attempt on this report to show all types of defects encountered. This report merely shows the major causes of rejections.

We have found that top management is concerned not only with these two reports but is also very much interested in the progress of the Corrective Action Committee. We have found it advisable to send copies of the Corrective Action Committee meetings to top management. We have followed one general rule in reporting to top management. This may be stated briefly as follows: The report must be accurate and should be as brief as possible. Reports of this type should not include the complete data and calculations. These reports should be expressed simply by means of charts and/or bar graphs. If this simple rule is followed, we believe a more active control program is possible and one in which top management is continually interested.

Quality control of sub-assemblies boiled down to the bare essentials is composed of the following:

1. Study of existing quality standards.
2. Study of existing operations and processes.
3. Analysis of existing inspection procedures and records.
4. Gathering of preliminary data and preparation of control charts.
5. Reducing the program to writing.
6. Securing the backing of top management.
7. Providing some method of securing corrective action.
8. Periodical reporting of results of the quality control program.

QUALITY INDEX PROGRESS RECORD
UDF-03-46

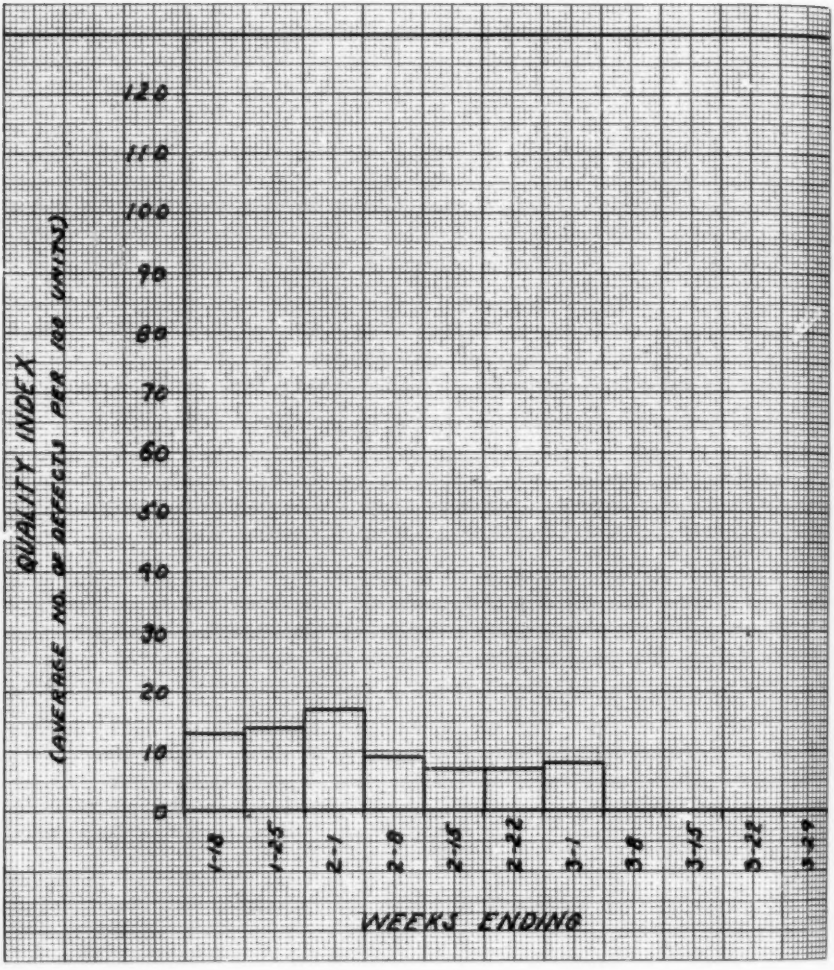


Figure 3

QUALITY RECORD--UDF-03-46
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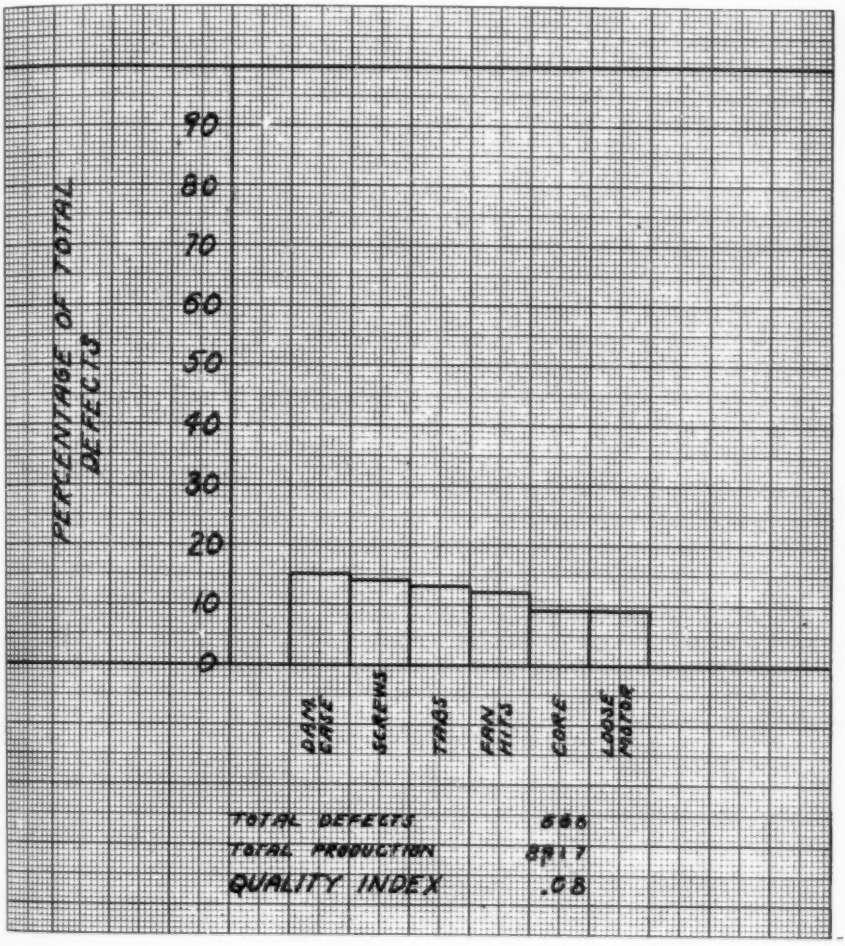

Figure 4

ACCEPTANCE SAMPLING BY VARIABLES

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1. Introduction. The designation "acceptance sampling" is applied to the procedure whereby an inspector makes a decision regarding the disposition of an aggregate of product on the basis of evidence obtained by examining a portion of the aggregate. If the decision regarding the acceptability of individual items is reached by noting whether or not they meet a given standard, without regard to the extent to which any item departs from the standard, the sampling is said to be "by attributes." If, on the other hand, the actual measurements of the items are taken into consideration, then the sampling is said to be "by variables."

As a result of the adoption of standard sampling techniques by the Army Service Forces and other procurement agencies, the methods of attributes acceptance sampling have become quite familiar to most manufacturers. But, in spite of the fact that numerous scientific sampling plans based on measurements were devised and put in operation during the war, the methods of acceptance sampling by variables do not seem to be very well known in many places where they could prove advantageous. It is hoped that the present paper, by listing some of the basic principles and by outlining the solutions for a few of the simpler problems, may be of some help in providing a better understanding of this type of acceptance sampling and in promoting a wider utilization of its techniques.

2. General principles. The methods of acceptance sampling by variables are, to a considerable degree, a direct extension of those used in the attributes case. A lot-by-lot sampling plan for attributes is determined, ordinarily, with reference to an acceptable quality level (AQL) and a lot tolerance percent defective (LTPD) together with the producer's risk of having satisfactory product rejected and the consumer's risk of having sub-standard lots accepted. For example, we might have AQL = .005 and LTPD = .05 with a producer's risk of 5% when his process is controlled at $p_1 = .005$ and a consumer's risk of 10% that lots with a fraction defective, $p_2 = .05$, will be accepted. The single-sampling plan which specifies acceptance of any lot when not more than one defective is discovered in a sample of seventy-five units is one which approximately satisfies these requirements.

A convenient device for depicting the character of any sampling plan is the operating characteristic curve (OC). In Figure I we have the operating characteristic curve for the plan $n = 75$, $c = 1$. It is worth noting that the producer's risk for lots with a fraction defective of less than .005 is less than 5% and that the consumer's risk for lots with a fraction defective greater than .05 is less than 10%. The slope of the curve at the point corresponding to 50% acceptance is a rough measure of the discriminatory power of the plan. The steeper the slope the smaller the difference between the fraction defective for which 90% of the lots are rejected and the fraction defective at which 95% are accepted. The plan $n = 2500$, $c = 18$, for example, has a producer's risk of 5% at $p_1 = .005$ but has a consumer's risk of 10% at $p_2 = .01$ rather than at $p_2 = .05$. This improvement is obtained, of course, at the cost of an increase in sample size.

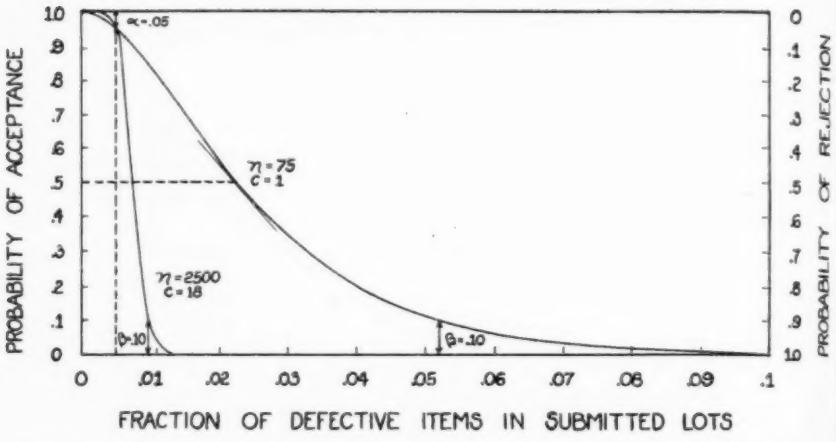

FIG. I - OPERATING CHARACTERISTIC CURVES FOR SINGLE SAMPLING PLANS: (1) n = 75, c = 1; (2) n = 2500, c = 18.

A possible adaptation to the case where acceptance sampling is based on measurements is entirely apparent. Let us suppose that a tensile strength above 100,000 pounds per square inch is considered satisfactory and a tensile strength below 100,000 p.s.i. is unsatisfactory. Then we might decide that lots from a universe containing five-thousandths of its tests below 100,000 p.s.i. (p_1 = .005) would be acceptable and that lots from a universe containing five-hundredths of its tests below 100,000 p.s.i. (p_2 = .05) should be rejected. For the producer's and consumer's risks of 5% and 10% respectively, the plan n = 75, c = 1 would be technically correct. The application would be as follows: Pull 75 tensile tests; if not more than one of them is below 100,000 p.s.i., accept the lot.

Under some circumstances this procedure might be practical but it has at least one weakness. It does not make efficient use of the information obtained by measuring the tensile strength.

Before amplifying this point it might be well to say a word about frequency distributions, the parameters which characterize them, and the sampling distributions of certain statistics which can be calculated from samples. In the discussion which follows, we shall use x to denote a continuous variable (such as tensile strength). Also

$\int_a^b f(x)dx$ = probability that $a \leq x \leq b$ in the universe of values of x under discussion,

m = average value of x in the universe,

σ_x = standard deviation of x in the universe,

$\bar{x}$ = average of a sample of n measurements drawn at random from the universe,

s = a statistic, calculated from the sample, which is used to estimate σ_x,

R = difference between largest and smallest value in a sample of n measurements,

$u = (\bar{x} - m) \div (\frac{\sigma_x}{\sqrt{n}})$,

δ = an arbitrary constant,

$w = \frac{s^2}{\sigma_x^2}$,

$t = \frac{u + \delta}{\sqrt{w}}$, when u and w are calculated for a sample from a normal universe,

$G = (u + \delta) \div (\frac{R\sqrt{n}}{\sigma_x})$.

We note that, for $\delta = 0$,

$t = \frac{\sqrt{n}\ (\bar{x} - m)}{s}$, and

$G = \frac{\bar{x} - m}{R}$.

Whenever $f(x) = \frac{1}{\sigma_x \sqrt{2\pi}}\ e^{-\frac{(\bar{x} - m)^2}{\sigma_{\bar{x}}^2}}$, then the variable x is said to be "normally" distributed or to have the Gaussian distribution. From tables of the normal integral which are readily available, (For instance, Freeman, [1] p. 166; square brackets refer to bibliography at end of paper) it is possible to find the probability that x will have a value between any specified limits. For example, practically all (99.73%) of the values of x can be expected to lie in the interval $(m - 3\sigma_x,\ m + 3\sigma_x)$. Also 99.5% of the values will be above $(m - 2.58\sigma_x)$ or 95% above $(m - 1.65\sigma_x)$.

The importance of normality stems partly from the amount of information available regarding the distributions of several useful sample statistics (such as s, t, and R), when the samples can be assumed to have been drawn from a normal distribution. It is well known that the sample mean, $\bar{x}$, is normally distributed when the parent population is normal. Furthermore, the distributions of means of samples from almost all universes tend to normality as the sample size increases. This latter fact leads to the practical assumption that for $n \geq 4$, u is normally distributed with a mean of zero and a standard deviation of unity.

Simply because the distribution of a finite set of values is fairly symmetrical, it would be unwise to assume that the universe of origin was normal. It seems clear that many distributions met in industry are skew. Some small departure from normality, however, does not appear to seriously prejudice results obtained in practical situations. If the departure is great, as judged from available tests, then the formulas based on the normality assumption should be used with caution.

3. Lot-by-lot acceptance when the percentage non-conforming is specified. Let us return now to the general problem of devising a sampling plan such that the risk of accepting a universe having 5 tensile tests out of 100 below 100,000 is 10% and the risk of rejecting a universe with only 5 tensile tests out of 1000 below 100,000 p.s.i. is 5%. For the time being let us make the simplifying assumption that the standard deviation of tensile strength is 4,000 p.s.i. (We shall discuss the validity of such an assumption later.) When the mean tensile strength in the universe is m, then ½% of the tests fall below $m_1 - 2.58\ \sigma_x$ (assuming normality). Setting this expression equal to 100,000 and inserting the value assumed for m, we have

$$m_1 - 2.58\ (4{,}000) = 100{,}000,$$

$$\text{or } m_1 = 110{,}320. \qquad (3.1)$$

When the mean tensile strength is m_2, 5% of the tests fall below

$m_2 - 1.65\sigma_{\bar{x}}$, and $m_2 - 1.65\ (4000) = 100{,}000$,
or $m_2 = 106{,}600$. (3.2)

Now 5% of the means of samples of size n, drawn from a universe of mean 110,320 and standard deviation 4,000, fall below

$$110{,}320 - \frac{1.65\ (4{,}000)}{\sqrt{n}} = L_1. \qquad (3.3)$$

Also 10% of the means of samples of size n, drawn from a universe of mean 106,800 and standard deviation 4,000, fall above

$$106{,}600 + \frac{1.28\ (4{,}000)}{\sqrt{n}} = L_2. \qquad (3.4)$$

Equating L_1 and L_2, we find n = 9.9 and $L_1 = L_2 = 108{,}225 = L$. While we cannot measure tensile strength to the accuracy indicated, our plan in theory would be the following: Take the average of a sample of 10 tensile measurements and reject whenever this average falls below 108,225 p.s.i. This number of tests compares favorably with the previous stipulation of 75.

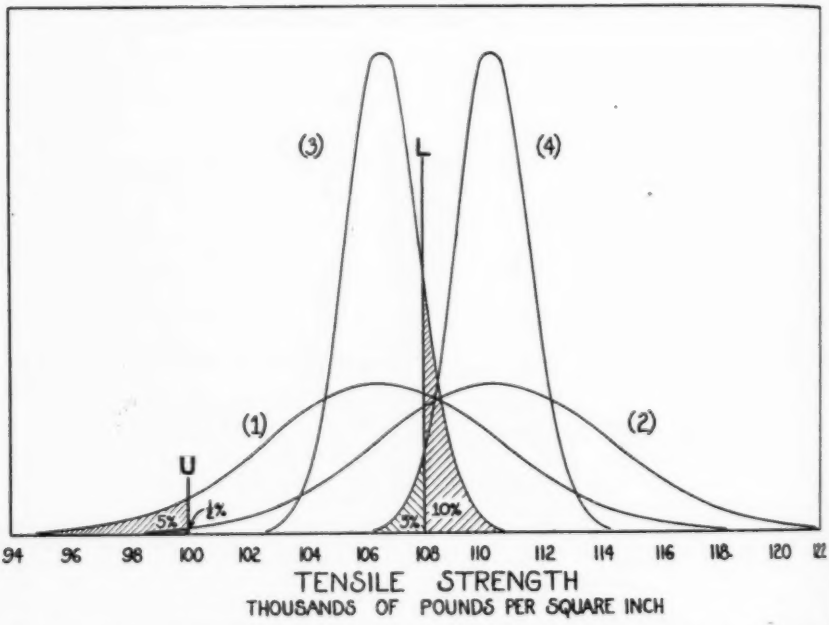

FIG. II - CURVES ILLUSTRATING CHARACTERISTICS OF SAMPLING PLAN DESIGNED TO DISCRIMINATE BETWEEN ACCEPTABLE AND UNACCEPTABLE LOTS OF TENSILE TESTS (STANDARD DEVIATION ASSUMED TO BE 4,000 p.s.i. FOR DISTRIBUTIONS OF INDIVIDUAL TESTS):

(1) DISTRIBUTION OF UNACCEPTABLE LOT OF INDIVIDUAL TESTS (5% BELOW 100,000 p.s.i.);
(2) DISTRIBUTION OF ACCEPTABLE LOT OF TESTS (½% BELOW 100,000 p.s.i.);
(3) DISTRIBUTION OF SAMPLES OF TEN FROM UNACCEPTABLE LOT (10% ABOVE 108,225 p.s.i.);
(4) DISTRIBUTION OF MEANS OF SAMPLES OF TEN FROM ACCEPTABLE LOT (5% BELOW 108,225 p.s.i.).

Study of Figure II should serve to clarify the reasoning used. Curve (2) is a normal curve with σ_x = 4,000 and with its mean at 110,320. Since the value 100,000 is 2.58 standard deviations to the left of the mean, ½% of the individual tests can be expected to fall below 100,000. With reference to the mean of Curve (1), the value 100,000 is 1.65 σ_x to the left and, therefore, 5% of the tests from the universe represented by Curve (1), are expected to fall below 100,000. The curve of means, Curve (4), for samples of 9.9 (or 10) from the universe of Curve (2) has 95% of its area above L. Therefore, if samples come from the universe of Curve (2) and we reject for an average below L, we would reject only 5% of the time. Likewise the curve of means, Curve (3), for the other universe has 90% of its area below 100,000. Therefore, 90% of the lots like Curve (1) will be rejected.

If, instead of substituting σ_x = 4,000, we make the above calculation in terms of σ_x, we find

$$n = 9.9$$
$$L = 100{,}000 + 2.06\sigma_x. \qquad (3.5)$$

It may be surprising to discover that n does not depend on σ_x.

If σ_x is underestimated, L is lowered and, from Figure II, it is quite obvious that the producer's risk is lowered and the consumer's risk is increased. It might also be noted that an increase in sample size decreases both risks. Therefore, if there is lack of confidence in the estimate of σ_x, one may "hedge" by increasing the sample size.

Where the sampling plan is based on a known value of σ_x, it would be well to run a control chart on either standard deviation or range in samples in order to check on the accuracy of the knowledge. If σ_x is not well known then this lack of knowledge should be recognized in the construction of the plan. Dr. W. A. Wallis, in a paper to be published by the American Statistical Association [2], has given a method for use in this situation. He determines n and k, so that when the lot is accepted or rejected on the basis of

$$\bar{x} + ks \geq U,$$
or $$\bar{x} + ks < U,$$

the correct risk criteria are met. In our case U = 100,000, k = -2.06 and n = 30.9. In the previous case, when σ_x was known, we drew a sample of 10, calculated $\bar{x}$ and accepted the lot for

$$\bar{x} - 2.06\sigma_x \geq 100{,}000.$$

In the latter case, we draw a sample of 31, calculate $\bar{x}$ and s, and accept for

$$\bar{x} - 2.06s \geq 100{,}000.$$

In a paper [3] published in the Supplement to the Journal of the Royal Statistical Society, Jennet and Welch point out that the quantity

$$z = \bar{x} + ks$$

is nearly normally distributed with a mean,

$$\bar{z} = m + ka\sigma \qquad (3.6)$$

and a standard deviation

$$\sigma_z = \sigma\sqrt{\frac{1}{n} + \frac{b^2 k^2}{2(n-1)}}, \qquad (3.7)$$

where a and b depend on the sample size. In Wallis' paper, he makes use of the fact that a and b tend rapidly to unity and also replaces (n -1) by (n) in the denominator of the second fraction under the

radical sign above. In effect he uses the approximations,

$$\bar{z} = m + k\sigma$$

and $$\sigma_z = \sigma\sqrt{\frac{1}{n} + \frac{k^2}{2n}} = \frac{\sigma}{\sqrt{n}}\sqrt{1 + \frac{k^2}{2}} . \qquad (3.8)$$

If lots are acceptable when $\frac{1}{2}\%$ of the tests fall below 100,000, the acceptable population mean is given by

$$m_1 = 100{,}000 + 2.58\sigma \qquad (3.9)$$

and the acceptable population mean for z is given by

$$z_1 = 100{,}000 + 2.58\sigma + k\sigma. \qquad (3.10)$$

But, in order for 95% of the samples of size n to have

$$\bar{x} + ks \geq 100{,}000$$

when the samples are drawn from acceptable lots, we must have

$$z_1 = 100{,}000 + 1.65\sigma_z. \qquad (3.11)$$

Thus the equation,

$$2.58\sigma + k\sigma = \frac{1.65\sigma}{\sqrt{n}}\sqrt{1 + \frac{k^2}{2}} \qquad (3.12)$$

must be satisfied.

From a similar consideration for unacceptable lots (where 5% of the tests are below 100,000 and where the risk of acceptance is to be 10%) we get a second equation

$$1.65\sigma + k\sigma = -\frac{1.28\sigma}{\sqrt{n}}\sqrt{1 + \frac{k^2}{2}} . \qquad (3.13)$$

Solving the two equations simultaneously we get $k = -2.06$ and $n = 30.9$.

Making use of tables given by Johnson and Welch in Biometrika, Vol. 31, [4], the problem can be solved without assuming the normality of z, but the computations are somewhat lengthy.

We have noted that, for our problem, the sample size when sigma is known is less than one-third that necessary when sigma is not known. In an article [5] published in the Journal of the American Statistical Association in 1936, Neyman and Tokarska (p. 325) note as follows:

> "Since the publication of the well known book of Shewhart there will be scarcely any larger works which would not apply to the modern methods of inspection. We may therefore assume that the manufacturer knows approximately the value of the standard deviation, σ_0, of the character, x, of single units he is delivering and also that he is able to direct the process of manufacturing so as to obtain consignments with the average value of this character having approximately any desired (and attainable) value, a."

Although the paper was written in England, one cannot avoid the feeling that this statement expressed a hope rather than a conviction. Even in the year 1947, it is doubtful that such a statement about manufacturers in the United States would be strictly accurate. It would be useful, however, if, not only the producer, but also the consumer knew the standard deviations for the quality characteristics of products to be inspected by sampling methods.

4. Lot-by-lot acceptance when the mean is specified and the standard deviation is known. Returning to the solution of our original problem (where the standard deviation was assumed to be known) we

notice that the specifications, as set, were equivalent to specifying the means of acceptable and unacceptable universes. For discrimination on the basis of means, sequential analysis provides an approach which usually results in economy in sampling. Suppose we consider its application. Our conditions are $m_1 = 110{,}320$, $m_2 = 106{,}600$, $\alpha = .05$, $\beta = .10$, $\sigma = 4{,}000$. This means that when the universe average is 110,320 we are willing to take a one-in-twenty chance of rejection, and when the universe average is 106,600 we are willing to take a one-in-ten chance of acceptance. The method, as developed by the Statistical Research Group at Columbia and described in Sequential Analysis: Applications [6] is as follows: We determine two limits L_1 and L_2 which are functions of n. Measurements are made one-by-one. If, at any time, the sum of the measurements is greater than L_1 we accept the lot. If the sum is less than L_2 we reject the lot. Otherwise we continue sampling.

For our problem

$$L_1 = 108{,}460n + 9{,}682,$$
$$L_2 = 108{,}460n - 12{,}432. \qquad (4.1)$$

When $m = m_1 = 110{,}320$, or $m = m_2 = 106{,}600$, the average number of tests necessary for a decision is between 5 and 6.

5. Risks inherent in using very small samples. It is useful to give brief consideration to the operational meaning of inspection specifications. An example of one common directive is the following: Pull one tensile test. If it is above 100,000 p.s.i., accept the lot. If it is below 100,000 p.s.i., pull two more tests. If both are above 100,000 p.s.i., accept the lot; otherwise, reject the lot.

If the mean of the lot of tests is m and the standard deviation is σ, then, on the assumption of a normal distribution, the probability, p, for a test below 100,000 can be obtained from tables. It is evident that the probability of acceptance is given by

$$P = (1 - p) + p(1 - p)^2 = 1 - 2p^2 + p^3. \qquad (5.1)$$

For $P = .95$, $p = .165$, $m = 103{,}896$,
for $P = .10$, $p = .908$, $m = 94{,}432$,
and for $P = .50$, $p = .597$, $m = 99{,}124$.

The values of the mean are found on the assumption that $\sigma = 4{,}000$.

These results indicate that, when the mean tensile strength for the lot is 104,000, it will be accepted 19 times out of 20; when the mean is 99,000, the lot will be accepted half of the time; when the mean is 94,000, the lot will be accepted 10% of the time. It should be remarked that, when more and more retests are allowed, the percentage of below-standard material which will be accepted, if offered, increases from 10% toward 100%.

Actually, the above plan is the double sampling plan $n_1 = 1$, $c_1 = 0$, $n_2 = 2$, $c_2 = 1$, where tests below 100,000 are rated as defectives. Before placing dependence on the discriminatory power of this plan, the inspector should study the operating characteristic curve constructed by plotting P against p from the equation given above. Recently the British Standards distribution issued a "Memorandum on sampling clauses in specifications for manufactured articles." In the introduction ([7], p. 2) the situation regarding small samples based on fraction defective is nicely summarized as follows:

"Specifications for manufactured articles have mainly relied, up to the present, for the maintenance of quality upon sampling clauses of conventional type. Such clauses require a sample of from two or three to ten articles of which not more than a stated number must fail.

It is now widely known, that in themselves, such small samples of ten or less offer little security as to quality and it is not too much to say that, where articles are accepted upon the results of these small samples, the quality accepted is virtually whatever happens to be offered by the producer.

In the light of the spreading of this knowledge, it is desirable that sampling clauses of British Standards should be prepared in accordance with accepted modern methods of sampling and that the sampling requirements of published standards should be reconsidered, as opportunities occur."

6. The inspection lot. In the foregoing discussion it has been emphasized (1) that risks represent probabilities, (2) that samples are assumed to be random samples, and (3) that each lot constitutes a universe. The phrase "a lot of tensile tests" has been used repeatedly. It is natural to think in terms of the acceptance or rejection of some unit, such as a heat of steel, a coil of wire, a carload of cement, or a shipment of paper. Let us consider Col. Simon's important article [8] on "The Industrial Lot and its Sampling Implications." In it he defines the lot as "an aggregation of articles which are essentially alike." He calls attention to the mistake of assuming that any "parcel of articles" is homogeneous with regard to the quality characteristic under consideration. He points out the fact that the statistician is prone to assume that the "parcel of articles" is a universe or population, in the technical sense, and to make inferences without bothering to test this crucial assumption.

In so far as acceptance sampling is concerned, the assumption that all articles in a lot have been produced under essentially the same conditions would not be so dangerous if we had some assurance of being able to draw a sample in a random manner. In drawing a sample of tensile tests from the millions of tensile tests which might be made on a heat of steel, it seems out of the question, however, to give every test an equal chance to be included in the sample. The best we can do is to use a control chart or equivalent procedure to assess the homogeneity of our results. A re-interpretation of Simon's Grand-lot Plan ([9], pp. 27-33) consists of dividing the conjectured lot into sub-lots, sampling each sub-lot, plotting results on a control chart, and accepting the conjectured lot as being a lot only if the results do not show excessive variabilities.

The author has examined a number of government specifications which include directions on the manner of sampling for inspection. Some of those written more than three years ago are inclined to define a lot as not more than n units of the same type offered for delivery at the same time, (where n might be 3,000, for example). Later specifications are more careful. One concerned with a steel product, for instance, directs increased testing when the units are not grouped by heats.

A general directive [10] issued by the Bureau of Ships in May, 1945, to all Inspectors of Naval Material, has this to say on the subject of "Lot."

"F-1a. Lot.

(1) This subparagraph defines an 'inspection lot' or 'sampling lot', as distinct from the various other 'lot' concepts associated with the manufacturing process, or the order, or the contract, or the shipment, etc. The inspection lot may include material intended for delivery under several contracts or orders, provided that these contracts or orders all reference the specification in question.

(2) The proper formation of inspection lots is of great importance in the successful application of statistical lot acceptance sampling plans. The general principle to follow is that the inspection lot should be made as uniform as possible, and at the same time as large as possible, consistently with the specification requirements. Some suggestions for securing uniformity which are applicable in a number of cases are as follows:

(i) The material in a lot should, if possible, be produced continuously in the plant under essentially the same conditions.

(ii) When material is handled and inspected in the plant in some well-defined unit, such as a batch, dryer-load, press load, cure, bale, melt, heat-treatment, control lot, etc., consideration should be given to the possibility of making this unit the inspection lot.

(iii) If raw material used in a product comes from several suppliers of unequal merit, consideration should be given to the possibility of including material from only one supplier in the inspection lot.

(iv) If the products of different assembly lines are clearly of unequal quality, consideration should be given to the possibility of forming different inspection lots for different assembly lines.

(3) Where the inspection lot is defined to be all material from a batch or melt, it is not necessary that the entire lot, as so defined, be intended for delivery to the Navy. It is implied in such a case that when such an inspection lot has been inspected and found satisfactory, later deliveries may be made from it without additional testing, provided that the material can be positively identified."

7. Lot-by-lot acceptance when the mean is specified but the standard deviation is not known. Let us return to further consideration of the problem of acceptance when an acceptable universe average is specified but the universe standard deviation is not known. Suppose, for example, that we are concerned with acceptance of large lots of aerosol bombs where the acceptable average weight for the lot is 16 oz. and where we are willing to take a 1-in-20 chance of rejecting acceptable lots. Further, suppose that we decide to base our decision on

the result of weighing the contents of 3 bombs. How can we proceed when we have no information about the variation from bomb to bomb and when we are planning to treat each lot separately?

Assuming that weights are normally distributed with a mean of 16 oz. then, in samples of 3, the statistic,

$$t = \frac{\sqrt{3}\,(\bar{x}-16)}{s}$$

will be expected to fall in the interval (-2.92, 2.92) 90% of the time [11], and can be expected to be greater than (-2.92), 95% of the time. (We notice that if sigma were known then

$$u = \frac{\sqrt{3}\,(\bar{x}-16)}{\sigma} \qquad (7.1)$$

would be expected to be above (-1.65), 95% of the time.) The statistic s is calculated from the relation

$$s^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1} \qquad (7.2)$$

We may express the probability relation more compactly by writing,

$$P_3\left\{\frac{\sqrt{3}\,(\bar{x}-16)}{s} > -2.920 \;\middle|\; m = 16\right\} = .95. \qquad (7.3)$$

Obviously this is equivalent to

$$P_3\left\{\frac{\bar{x}-16}{s} > -1.686 \;\middle|\; m = 16\right\} = .95. \qquad (7.4)$$

If lots are accepted for

$$\frac{\bar{x}-16}{s} > -1.686$$

then the producer's risk of having lots with a lot mean of 16 rejected will be 5%.

It is interesting to investigate the consumer's risk of accepting lots with averages different from 16 oz. In particular, what is the risk of accepting lots with an average of 15 oz., (one ounce short)?

Unless some assumption is made regarding the value of the lot standard deviation the question cannot be answered. That such is the case follows directly from Dantzig's paper [12]. We can, however, quote risks for deviations expressed as a multiple of σ, and evaluate these risks later, when we arrive at some estimate of σ. For example, we find that if the true average is $16-\sigma$,

$$P_3\left\{\frac{\bar{x}-16}{s} > -1.686 \;\middle|\; m = 16-\sigma\right\} = .68. \qquad (7.5)$$

The problem of testing the significance of observed values of $[(\bar{x} - m_0) \div s]$ when the true population mean is assumed to be $m_0 + \lambda\sigma$ has been treated in papers by Neyman [13], Neyman and Tokarska [5], Jennett and Welch [3], Johnson and Welch [4], Craig [14], and Ferris, Grubbs, and Weaver [15]. If, in the expression for t given at the beginning of this paper, δ is set equal to zero, the distribution of t is the well-known central t-distribution. If δ is not zero, the distribution of [5] is called the non-central t-distribution. When the

true population mean is assumed to be m_1, we write

$$t = \frac{\sqrt{n}\,(\bar{x} - m_0)}{s} = \frac{\sqrt{n}\,(\bar{x} - m_1)}{s} + \frac{\sqrt{n}\,(m_1 - m_0)}{s}. \tag{7.6}$$

Then $$\delta = \frac{\sqrt{n}\,(m_1 - m_0)}{\sigma x}. \tag{7.7}$$

Tables and graphs for testing the significance of t for specified values of δ and n will be found in the above-mentioned papers. Using an entry from Table I of Neyman and Tokarska ([5], p. 322), we find that

$$P_3\left\{\frac{\bar{x} - 16}{s} > -1.686 \,\middle|\, m = 16 - 2.78\sigma\right\} = .10. \tag{7.8}$$

In 1932, Dodge proposed [16] the use of $[(\bar{x} - m) \div R]$ for testing the hypothesis that the population mean is equal to m. Daly, in a recent paper [17] has given the distribution of a statistic G, where

$$G = (u + \delta) \div \left(\frac{R\sqrt{n}}{\sigma x}\right). \tag{7.9}$$

As noted above, we have

$$G = \frac{\bar{x} - m}{R} \tag{7.10}$$

when $\delta = 0$. Applying Daly's work to the solution of our bomb problem, we note that

$$P_3\left\{\frac{\bar{x} - 16}{R} < -.88 \,\middle|\, m = 16\right\} = .05, \tag{7.11}$$

$$P_3\left\{\frac{\bar{x} - 16}{R} > -.88 \,\middle|\, m = 16 - \sigma\right\} = .68. \tag{7.12}$$

Daly points out that good approximations for the upper 5% points for the distribution of central G can be obtained from the upper 5% points of t in a manner which we will illustrate with a specific example. We note that

$$P_3\left\{\frac{\sqrt{3}\,(\bar{x} - 16)}{s} > 2.92 \,\middle|\, m = 16\right\} = .05. \tag{7.13}$$

Using the familiar relations

$$E(R) = c_2\sigma$$

$$E\left(\sqrt{\frac{\Sigma(x_i - \bar{x})^2}{n}}\right) = d_2\sigma, \tag{7.14}$$

where E indicates expected (or average) value,

we have $$E\left(\frac{s}{\sqrt{n}}\right) = \frac{c_2\sigma}{\sqrt{n-1}} = \left(\frac{c_2}{\sqrt{n-1}}\right)\cdot\left(\frac{E(R)}{d_2}\right). \tag{7.15}$$

For n = 3, we have $c_2 = .7236$, $d_2 = 1.693$, and $E\left(\frac{s}{\sqrt{3}}\right) = (.3023)\cdot E(R)$.

Using the relation between expected values as the true relation, we replace $s/\sqrt{3}$ by .3023R in the above probability relation, obtaining the approximation,

$$P_3\left\{\frac{\bar{x} - 16}{R} > .883 \,\middle|\, m = 16\right\} = .05. \tag{7.16}$$

According to Daly, the exact relation would be

$$P_3\left\{\frac{\bar{x} - 16}{R} > .88 \,\middle|\, m = 16\right\} = .05. \tag{7.17}$$

8. Use of control charts in acceptance sampling. Up to this point our attention has been focused on lot-by-lot acceptance. Since the information which can be obtained from any individual sample is likely

to be meagre, serious consideration should always be given to the possibility of combining results by use of the Shewhart methods. Inspection usually has the dual purpose so well described in the A. S. A. manual [18]. We desire information in order to decide whether both product and process are satisfactory. When a process is controlled at a satisfactory level our assurance regarding product quality is far greater than when we treat each isolated lot as a separate entity and try to assess its quality without using the valuable collateral information so readily available. When other conditions are comparable sampling efficiency increases with sample size. If a sample of ten units is drawn from each of 40 lots and if no lack of control is indicated then we have the advantage of a sample of 40 times 10 or 400 to guide us in the disposition of the super lot.

The use of control charts for acceptance sampling by variables is so well known that it needs no description in this place. The method is carefully explained in Chapter VI of Colonel Simon's An Engineers' Manual of Statistical Methods [9] and has been widely used. Schrock's work at Aberdeen in connection with the testing of armor plate and that of Wells at Carnegie Institute of Technology on acceptance specifications for gun tubes are among the many successful applications which might be cited. (Also see [19], [20], [21]).

9. Conclusion. Needless to say, this paper constitutes, by no means, a complete treatment of the subject of acceptance sampling by variables. It has endeavored, however, to outline the solutions for a few of the acceptance problems which are commonly met in industry. The cost of inspection must always be balanced against the cost of errors in making decisions. By the use of simple statistical principles it is possible to design plans such that the probabilities for the rejection of good lots and the acceptance of bad lots can be accurately determined. Thus satisfactory estimates of the various costs can be made and the maximum economy consistent with good business principles can be attained.

Hit-or-miss inspection methods usually are unnecessarily expensive and sometimes are dangerous. Whether the methods discussed here are used or other procedures are developed, it is imperative that careful and enlightened analysis of sampling plans be made before they are installed as inspection tools.

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STATISTICAL TECHNIQUES FOR RESEARCH AND DEVELOPMENT

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The applications of statistical methods in chemical research and engineering development do not differ in principle from their use in conventional quality control. In both process and inspection quality control, and in research, we are concerned with testing hypotheses and with estimation of parameters, though the latter is probably a relatively more important function in research than in control work. In practice the close theoretical tie is carried further since one of the chief merits of quality control lies in its direction of research to improve the weak points of the process or product. Research application of statistical methods has the handicap that the techniques cannot be reduced to routine procedures to as great an extent as has been done with various sampling plans for quality control. The research worker must therefore emphasize the technical aspect of statistical methods, though he is perhaps fortunate in being less frequently confronted with those vexing psychological situations so common in the day of every quality control engineer.

The applications of statistical methods to research work constitute a very important adjunct to the scientific method and are perhaps truly identical to the scientific method in philosophy. Our applications of statistics can be classified into four broad categories:

1. Problems of condensation.
2. Problems of reliability.
3. Problems of correlation.
4. Problems of experimental design.

The problems of condensation by use of averages, standard deviation, etc. are so well known and similar in all fields that it is perhaps not worth while to discuss them in relation to our work. However, I should like to present a few typical examples of how we have approached problems in the other three classifications.

Reliability-Table I shows the flexural strength of two laminates prepared by polymerizing at 100°C and 120°C a vinyl type monomer which had been soaked into a reinforcing material and assembled into a laminate.

Table I

A: Psi Flexural strength, (100°C polymerization)	B: Psi Flexural strength (120°C polymerization)
15,950	18,100
16,500	17,450
16,230	17,920
16,800	17,600
16,750	18,000
$\bar{x}$ = 16,450 ± 320	$\bar{x}$ = 17,810 ± 247
σ^2 = 128,330	σ^2 = 76,480
σ = 358.23	σ = 276.55

$$2\sigma_{(\bar{x}_{100} - \bar{x}_{120})} = 2\sqrt{\sigma^2_{\bar{x}_{100}} + \sigma^2_{\bar{x}_{120}}}$$

$$= 405.$$

$$\bar{x}_{120} - \bar{x}_{100} = 1360 \pm 405$$

This method of placing fiducial limits not only on the average flexural strengths but also on the difference between them seems more meaningful than to merely make the conventional t test. Thus, in the example above we not only determine if a difference in polymerization temperature causes difference in flexural strength, but also we quantify that difference as being at least 955 psi and not more than 1765 psi. If the maximum difference is not important in an engineering sense, we do not concern ourselves with controlling polymerization temperatures within the 100°C-120°C range.

Another reliability problem we frequently encounter is the calculation of the reliability of a function calculated from variable physical and chemical measurements. An example of this is the determination of the intrinsic viscosity of polymers from effluence time of a polymer solution through an orifice of specified dimensions. The variable measurement is the time of effluence of a specified volume of solution and the intrinsic viscosity is a function of this time. The mathematics involved are not complicated:

Let $u = f(x,y,\ldots)$.

Then $$\sigma^2_u = \left(\frac{\partial u}{\partial x}\right)^2_y \sigma^2_x + \left(\frac{\partial u}{\partial y}\right)^2_x \sigma^2_y + \ldots$$

Table II shows how the reliability of intrinsic or inherent viscosity is calculated from time of effluence measurements. T_o is the effluence time of the pure solvent and T is the effluence time of a .5 per cent polymer solution in that solvent. C is a constant dependent upon the concentration of the polymer solution.

Table II

T	T_o
255.0	176.3 sec.
255.2	176.6
256.0	176.8
256.2	176.9
256.8	177.0
average 255.8	176.7
variance .00548	.000775

C = .5 gm/100 gm

$$\eta \text{ (inherent viscosity)} = \frac{1}{C} \ln\left(\frac{T}{T_o}\right)$$

$$\sigma^2_\eta = \frac{1}{C^2}\left[\frac{1}{\bar{T}^2_o}\sigma^2_{\bar{T}_o} + \frac{1}{\bar{T}^2}\sigma^2_{\bar{T}}\right]$$

$$= \frac{1}{(.5)^2}\left[.000\,000\,108\right] = .0000434$$

$$\text{reliability} = \pm 2\sigma_\eta = \pm .013$$

Correlation. I use the term correlation in a very broad sense and include, besides simple linear correlation, such techniques as analysis of variance, least squares regression techniques, polynomial curve fitting, multiple correlation, serial correlation, and partial regression analyses. This imposing list of correlation techniques is likely to intimidate the neophyte, but I feel that the ability to use them should be considered a necessary part of the professional equipment of every well trained engineer and scientist. They are basic techniques in using the experimental method to uncover new information.

% Styrene	0	10	20	30	40	50
Viscosity	45.7	28.0	22.0	9.9	11.1	10.3
	46.8	29.8	23.0	13.0	13.0	11.1
	49.9	31.0	24.0	14.3	14.0	12.0
	51.2	32.0	24.8	15.5	14.8	12.8
	52.5	31.5	26.5	17.9	16.9	13.6
Averages	49.2	30.5	24.1	13.7	14.0	12.0

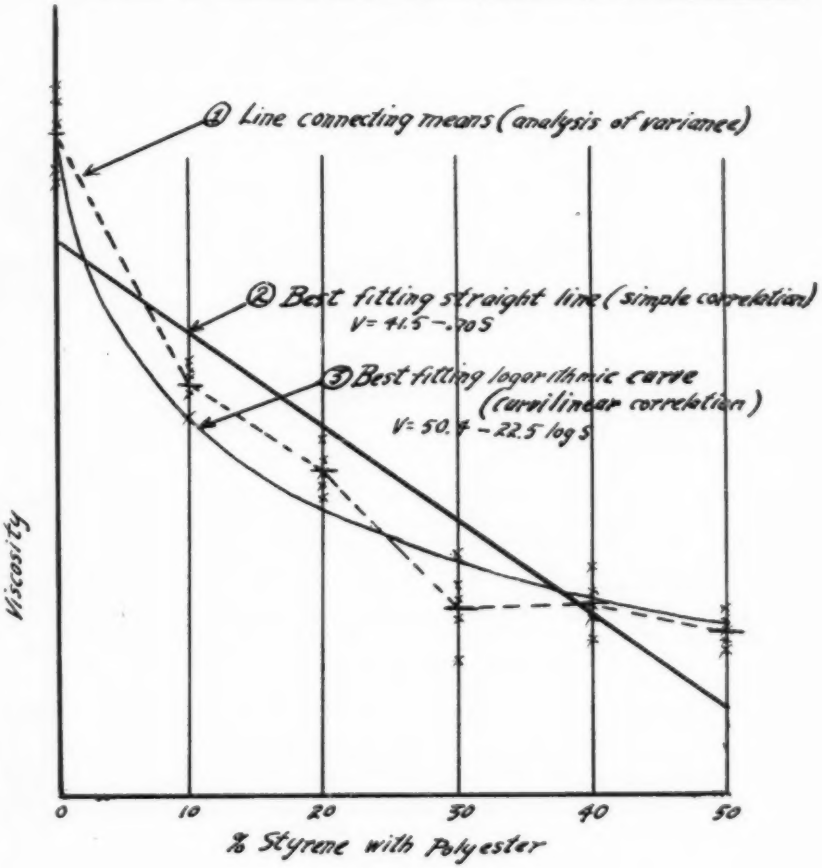

Figure I

Some of the basic principles involved in these techniques may be brought out by considering Figure I where 5 viscosity measurements have been made of a polyester monomer and of 5 different mixtures of the polyester with styrene.

Three lines have been drawn on the figure. The first connects the means of the viscosity measurements of each mixture. This is the line considered in analysis of variance, and if the irregularities of the line are greater than would be expected from the variabilities of individual measurements within one mixture, we accept as true that some

law of cause and effect (or relationship) exists, and seek to find it. The second line is that obtained by calculating a least squares linear regression line, and is the first attempt to quantitatively define the law relating viscosity with per cent styrene in the mixture. The simple correlation coefficient is the measure of relationship on the basis of this straight line. The third line is obtained by calculating the best fitting logarithmic curve. This curved line is closer to giving a complete description of the relationship than the straight line, and a higher correlation coefficient ($r = -.958$) will be found by pairing the logarithmic functional values of per cent styrene with viscosity than was obtained by the straight pairing of values for the simple correlation coefficient ($r = -.908$).

Multiple correlation and partial regression are techniques particularly valuable in handling observational data from a process where the variables can not be manipulated at will. By these methods the analysis enables the experimenter to consider each variable independently as well as in conjunction with the other variables and hence provides a powerful technique in the hands of a well informed experimenter to unravel complex and difficult controllable variables affecting process yields and product quality.

Serial correlation is a technique for exploring for significant cyclic variations, observational data obtained in a particular sequence. This technique provides a way of evaluating trends and periodic fluctuations in process yields and quality.

Experimental Designs. Perhaps the greatest boon to scientific workers provided by statistical methods comes in the field of designing experiments. The clear cut requirement for an estimate of experimental error (which has long been recognized as primary in controlled experimentation) and the quantitative partition of data to test particular hypotheses and estimate particular parameters lead to care in designing experiments which are to provide data for statistical examination as a basis for making decisions.

In our work the "analysis of variance" techniques probably contribute more by way of insight into experimental design principles than by their intrinsic value as statistical techniques.

Two basic designs other than simple comparisons are used in our work, "Latin Square" designs and "factorial" designs. Table III is an example of the simplest and most commonly used latin square arrangement.

Table III

Flexural strength values (psi) of four sheet castings of a polymer.

Temp. of Polymer. Bath	Time of Polymerization: 20 min.	Time of Polymerization: 60 min.
100°C	I. 1% Catalyst: 9,500; 10,650; 9,700; 9,950; 10,100	II. 2% Catalyst: 11,900; 11,850; 11,850; 12,000; 12,100
120°C	III. 2% Catalyst: 10,550; 11,000; 11,100; 11,350; 11,200	IV. 1% Catalyst: 10,900; 11,500; 11,850; 11,700; 11,650

Averages:	
20 min.	10,510
60 min.	11,730
difference:	1,220
100°C	10,960
120°C	11,280
Difference	320
1%	10,750
2%	11,490
difference	740

$2\hat{\sigma}_{\bar{x}} = 294$: $2\hat{\sigma}_{\bar{x}-\bar{x}'} = 416$

In this experiment, the effect of three variables in the polymerization process have been evaluated. The arrangement is such that all four castings are used to evaluate the effect of each variable. Thus, castings I and IV may be averaged and compared with the average of II and III for catalyst concentration effect, I and II versus II and IV for polymerization bath temperature effect, and I and III versus II and IV for the effect of time in the polymerization bath. This combining of variables increases the generality of the results and gives a precision equivalent to that obtained by casting 4 sheets for each variable comparison, or 12 altogether.

However, the Latin Square does not evaluate the interaction between variables (though it does tend to average in these effects). In the example above, time in the polymerization bath may be important only at the lower bath temperature and perhaps only then with the smaller concentration of catalysts. These questions require a "factorial" experiment for their answer. In a factorial experiment each variation of each variable must be paired with every variation of the other variables. The number of experimental batches required is the product of the variations of each variable. A factorial design for the variables shown in table III will require 2 x 2 x 2 = 8 castings. Table IV shows the results of such an experiment.

Here the results of Castings I,II,III,IV have been supplemented by four additional castings which enable us to re-evaluate the main effects with greater precision and independently of the interactions which are evaluated separately.

The improved precision of the average effects of the variables is shown by comparing the reliability of the averages (±245 psi) based on 20 test specimens with that calculated in Table III (±294 psi) based on 10 test poises.

Table IV

Flexural strength values (psi) of eight sheet castings of polymer.

		Time in polymerization bath	
		20 min.	60 min.
100°C Bath	1% catalyst	I. 9,500 10,650 9,700 9,950 10,100 $\bar{x}$ = 9,980	V. 11,500 11,650 11,250 11,550 11,900 $\bar{x}$ = 11,570
	2% catalyst	VI. 11,800 11,750 11,800 11,950 11,900 $\bar{x}$ = 11,840	II. 11,900 11,850 11,850 12,000 12,100 $\bar{x}$ = 11,940
120°C Bath	1% catalyst	VII. 11,300 11,750 11,600 11,650 11,700 $\bar{x}$ = 11,600	IV. 10,900 11,500 11,850 11,700 11,650 $\bar{x}$ = 11,520
	2% catalyst	III. 10,550 11,000 11,100 11,350 11,200 $\bar{x}$ = 11,040	VIII. 9,900 10,150 9,400 9,800 9,900 $\bar{x}$ = 9,830

Averages:

20 min.	11,110
60 min.	11,215
difference	105
100°C	11,330
120°C	11,000
difference	330
1%	11,170
2%	11,160
difference	10

$2\hat{\sigma}_{\bar{x}} = 245$

$2\hat{\sigma}_{\bar{x}-\bar{x}'} = 346$

Interaction time-temperature = 373
Interaction time-catalyst = 328
Interaction temperature catalyst = 560
Interaction of time-temperature-catalyst = 45

The differences found in the Latin Square experiment are now seen to be largely due to interactions. Catalyst concentration differences are important at low temperatures and short cycles and at long cycles and high temperatures, but not at intermediate combinations of temperature and cycle. Stronger castings are generally obtained at 100°C than at 120°C but a high temperature-short cycle or a low temperature-long cycle combination give the best results. In general no difference is found between 1 per cent and 2 per cent catalyst, but when 1 per cent catalyst is used at low temperatures or when 2 per cent catalyst is used at high temperatures, poorer quality castings are obtained. No second order interactions are present which would involve effects between temperature, cycle, and catalyst independent of either primary variable effects or paired variable effects.

The practical aspect of the interaction evaluation is obvious. One can specify what combination of conditions are required to give a good casting for any values of the variables within the range covered in the experiment. An insight has been gained into the mechanism of the process that would not be possible by the common practice of holding all variables constant except one and running three comparative experiments, (Six castings in this case) one pair for each variable.

In conclusion, it should be admitted that while we commonly bring these various statistical techniques to bear on our experimental planning and results, we do not customarily accept the results of our calculation to be as reliable as statistical considerations alone would lead us to believe. Statistical considerations tell us the best they can be while our misinterpretations, biases, and bad luck can make them much worse.

IS YOUR INSPECTION DEPARTMENT INSPECTING?

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Back in 1914, prior to our entry into World War I, European contracts for ordnance material hit the United States in volume. One of the major arsenals in this country found itself in a critical situation through having severe degrees of rejected work. The art of quality control was still in its swaddling clothes. Go and no-go gauges were practically unknown; manufacturing required the services of many specialized crafts with considerable assembly and re-fitting; limits and tolerances were comparatively new ter s. The literature on quality control was practically non-existent - it simply consisted of a paragraph here and there in the industrial articles of that day.

In order to resolve the difficulties in the above-mentioned arsenal, Mr. George S. Radford was called in and succeeded in materially reducing the severity of rejections. But in so doing, he realized that efficient industrial and manufacturing effort called for something more than a consideration of limits, tolerances, and dimensions. The manufacture of a product with satisfactory characteristics required the control of many variables; consequently, he coined the term, "control of quality," and published his findings in an article that was the first comprehensive treatment of this phase of industrial management.[1] At the request of L. P. Alford and the American Society of Mechanical Engineers, Mr. Radford amplified and published his findings in 1922. This pioneer book, entitled Control of Quality in Manufacturing, Ronald Press, New York, comprehensively dealt with the principles of quality control and even included the use and limitations of statistics.

Many of the remarks to be made in the following paper derive their basis from this early material.

Differentiation between Inspection and Quality Control. Quality control, in some instances, has been very badly misused as a term in the intervening time. What were the early definitions of quality control and inspection?

> "Quality control is an administrative activity. It establishes characteristics desirable in a product, and maintains those characteristics economically and practically."
>
> "Inspection, on the other hand, is the agency used to bring to the surface deviation from desired characteristics."

Strictly speaking, inspection cannot create quality, for it does not remove or add metal or other characteristics of form utility. Inspection naturally brings, or is supposed to bring, facts to light; but then real quality control requires the creation of conditions that

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1. "Control of Quality in Manufacturing," Engineering, March, 1917.

produce uniformity. Consequently, quality control embraces a wide field of managerial effort that influences and is influenced by all phases and functions of an enterprise. Contrary to some thinking, quality control is not the eminent domain of the inspection group, but should govern throughout all phases of business from raw materials to the shipping floor and out into the hands of the consumer.

The Requirements for a Successful Enterprise. In the production section of the Department of Business and Engineering Administration at M.I.T., we have come to the conclusion that the phases or functions of a business are best catalogued by considering the requirements that a successful enterprise must meet. They are as follows:

1. The market - The promotion of an adequate and satisfactory outlet for a company's product.
2. Finance - The protection of the capital position of a company, with satisfactory profit margins.
3. Products - The establishment of products functionally and commercially desirable and capable of ready manufacture.
4. Facilities - Adequate tools for production and inspection with facilities for other associated activities, such as materials movement and storage.
5. Manpower - A satisfactory working force embraced with requisite skill, ability, and pride of craftsmanship.
6. Processes and Methods - Effective utilization of equipment and manpower.
7. Materials - Correct materials at the right time and in the proper quantity.
8. Unclassified - Such as union-management relationships, Federal restrictions, trade requirements, and so on.
9. Organization and Administrative Methods - The proper delegation of authority and responsibility for promoting and securing coordination of each of the above requirements.

Quality control, because of its permeating effects, can find opportunities for service in all phases of a business. As an example, using quality as a criterion, the opportunities for coordinated managerial effort may be amplified. A quality control chief can, therefore, evaluate his efforts in each of the above requirements and determine first, the opportunities for creating uniformity in quality, and secondly, improvements in quality. The question arises, why seek uniformity first and then improvement? An analogy may be taken with respect to cost control and reduction to clarify this point. If we are to secure adequate unit product costs, the first step is to obtain the means for determining and controlling the cost to certain limits. After this is achieved, naturally the next step can be the reduction of cost. The same way with quality control. The first attack should be upon variation, and when that variation is satisfactorily controlled, to limits that are practical under current conditions; then attacks may be made at those points where it is felt that changed requirements are desirable. The activities aligned with quality control in its entirety may properly lie within the juris-

diction of others rather than within the eminent domain of the quality control group, but the latter group can suggest, assist, or request the promotion of quality welfare throughout an organization. If this is to be done, however, the quality control chief must be able to talk as an equal with the people who design, build, and sell the product.

Financial Influences. Looking at the requirements of a business, where is the proper point to start as far as quality control is concerned? One of the major problems is the question of the cost of inspection.

The attention of a manager is constantly focused on indirect costs. Quality control chiefs are notorious in asking for more facilities, more and better inspectors--largely because they often do not have enough. On the other hand, a most apparent source of cost reduction for the manager is an examination of the number of inspectors that are on hand. Just like new product research and development, the majority of savings induced by quality control are of an intangible nature which cannot be measured except in the final result. How can we precisely evaluate in dollars and cents the contribution of research? In the same way, how is it possible to separate the contributions of quality control which are blended into the entire structure of a business? It would be interesting to make a check to verify if the companies that are the most successful, spend the most on inspection. Certainly this fact has been proved as far as new product development is concerned.

There are two approaches to this problem of cost: (1) Direct cost reduction by reduction of the inspecting force, a situation that may oftentimes throw a plant out of gear; and (2) indirect cost reduction by proper quality control expenditures, reducing the unit cost of the product. The old adage about spending money to make money applies here.

Naturally, the quality control chief has to work from both standpoints. He must directly save money by seeing that his facilities and manpower are fully utilized. However, he also has the opportunity of reaching an end objective of saving money by spending money. But if he takes this second approach, he must expand his service rather than remain merely in the role of inspector or observer. He must look at the unit product cost picture and point out periodically (1) how his group has increased or lowered the unit cost, and (2) how other groups are influencing the extent of his work in securing the proper degree of quality control. Approaching this on a plant-wide basis is oftentimes a very difficult task. Consequently, the quality control chief may often work out his considerations on a pilot basis, carrying through his improvements and suggestions on a product basis, isolating the conditions to a rather limited scale, rather than trying to attack the problem on a broad and over-all functional basis. With a recession coming up, the sooner this is done, the better. The quality control chief needs and requires proof of what he can do if he is to ward off direct cost reduction.

Another factor to be observed in cost is the dead hand of excessive and misdirected quality control of production. Machines down and waiting for inspection, heavy paper work, charting and calculations,

excessive adherence to incorrect standards, immobility of thinking on the part of quality control to get at the root of the trouble, particularly when reliance is placed only on finding someone to blame. The quality control chief has to contribute to the evaluation of the cost situation on bad points as well as good. The whole difficulty is proving the secondary benefits of quality control and keeping management from being penny-wise and pound foolish. Quality control is not expensive in itself; it is expensive to ignore.

The Role of Product Characteristics. In protecting the cost structure of a business, the process of elimination and simplification can be strongly applied to product characteristics to ease the quality control problem. Why hold something to a higher degree than is necessary? Quality control involves a search for lower specifications no less than tighter specifications. The following practices can be executed:

1. Evaluate the quality characteristics and coefficients to be sought--both from the standpoint of function desired on the part of the company, and secondly, from the standpoint of the market. Analysis of competitive products as well as your own enters in. Quality control people should know acceptance in the trade, have spotters, or at least get opinions to tell them what is going on.

2. Make certain each requirement is capable of ready measurement and of ready manufacture.

3. Then you are in a position to talk and adjust tolerances, limits, and dimensions in such a way that adequate compromises are developed to meet commercial requirements as nearly consistent with economical manufacture as possible. Coupled with these compromises are the following:

    a. Adequate location and registering surfaces that promote the ease of manufacture and serve to control the inspection of the pieces.

    b. Splitting of tolerances, giving leeway to those dimensions more difficult to hold. For example, if an allowable clearance is .008", rather than giving each mating part .004" leeway, one part could be held to .002" and the other to .006", making manufacturing easier.

    c. Questioning whether functional dimensions will be tightened when they reach the shop. Sometimes design engineers, having lack of confidence in shop ability, may tighten tolerances so as to protect themselves on the functionability of the product. This sort of practice may best be illustrated in concept by a Massachusetts speed law that says the maximum speed on a highway is thirty miles per hour, with the unstated hope that people will drive reasonably.

    d. Considering the role of standardization.

    e. Making certain that a change procedure promotes as adequate consideration of engineering change as is given to most parts when first going into production.

Promotion of Facilities and Processes. The tools of inspection have been tremendously improved over the past several years--magnified scales, utilization of complete, 100-per-cent automatic inspection. But there are many other opportunities, as follows:

1. Establishment of good housekeeping to promote orderliness and pride in facilities.

2. Physical planning of materials providing a service function by furnishing automatic count tote trays, two-bin or through-bin-materials handling, thereby insuring first in, first out, of materials, control of dispatching, and orderly segregation of good from bad pieces.

3. Revision of inspection stations to balance speed of catching difficulties with the required degree of inspection skill and utilization.

4. Equiping automatic machinery with automatic devices--pneumatic, hydraulic, electronic, and so on--to permit more time by operators for inspection.

5. Tooling of the machine with location surfaces and with dial indicators to make certain that machine conditions are right; for example, relation of work to jig, relation of jig to tools, relation of jig to table. An important role of tooling is to develop resources whereby an operator can know the machining conditions are such that a good product will invariably be turned out.

6. Use of a pilot shop to bridge the gap between experimental and actual volume production. Make your mistakes on a small scale. Try things out on a limited scale first. Actually, a procedure of this type saves time in the long run.

Concurrent with facilities, another requirement of business is to arrive at correct processing and methods. Naturally, inspection can and should be considered a part of the process. The periodic analysis of causes of defects will point out the need for technical improvements in processing, or at least the failure to maintain standard conditions originally set up.

Quality control is too often coupled with finding someone to blame and exercising disciplinary action when actually the correction should be technological in nature. For example, the inspection force in a steel mill in the Middle West was increased 15 per cent to check scale rolled into sheet steel. Actually, examination of process after a lengthy period of time disclosed that the steel was coiled hot after hot rolling, thus making slow heat dissipation that caused an extremely tough oxidized surface. The trouble was eliminated by reinstating heavy sprays at the final rolling stands.

Another technique as far as processing is concerned is to compare samples of parts made some time ago, feature with feature, with present output. Any new or changed aspects of quality will be thrown into highlight and call for investigation.

Sometimes technological change moves forward too rapidly. Various machining cuts are done in combination. Perhaps the trouble in quality

can be isolated by simplifying the operation. A methods engineer often sees the opportunity for more production, but has he realized that the removal or change of some portion of the process creates danger to quality? Degreasing operations are a good example. Naturally, a methods engineer looks for removal of degreasing as far as humanly possible, but this may cause a material effect in locating work in jigs or in actual machining.

Last, but not least, why is it not possible many times to arrive at the critical surfaces of machining first, concentrating inspection at points correspondingly, and reducing the danger of end spoilage after considerable work has been done? For example, too many times castings have been practically machined in entirety and poor surfaces have been disclosed at the very end. Machining naturally can be done in such a way that the surfaces that should be free of pores can be machined first, and disclosure made in such a way as to provide early rejection.

The Influence of Manpower. There is a basic precept adopted by the Remington Arms Company that highlights the role of this factor; namely, "quality cannot be inspected into the work." Quality is generated by proper standards and by proper facilities, and primarily, quality consciousness or pride of workmanship on the part of the operator. The trend today is progressively toward decentralizing inspection and getting it into the operator's hands. It excites the worker's interest, giving him a feeling of control over his work, not the machine over him.

Three steps are generally involved:

1. Creating quality consciousness first by showing the worker what happens if quality is off and why it is caused. As an example, demonstrations may be made whereby the worker is shown to what degree forcing of tools above recommended speeds actually cuts down on output rather than increasing it.
2. Training the operator to correct these difficulties.
3. Following up in a manner that quality consciousness on the part of the worker is recognized by management, other workers, and himself.

Fundamentally, what can be established is an incentive over and above what an operator gets in his pay envelope. Quality can always be discussed with a worker more so than quantity. He can more readily appreciate how a product that leaves his hands may influence the market. Discussions of quantity almost invariably brings up the problem of speed-up. Finally, in times of recession, the worker looks toward quality to maintain his job.

Associated with direct operator manpower, there is also the question of the inspectors themselves. Management too often assumes that quality consciousness does exist in their minds. In any case, the degree of craftsmanship certainly can be implemented by giving the inspectors the opportunity to learn the causes of defective work and simultaneously to learn correction rather than being mere automatons who measure or determine the levels of quality. Let them analyze the results and thus convert them from the idea that "I think this is the

trouble," to "I know that this is the trouble." Inspectors can prove to be extremely valuable when they have a voice in necessary correction.

Service to production may also be executed by the inspection group in such fields as salvage and repair, and many times by being in charge or oftentimes executing assembly work, thus contributing a direct and indirect service at the same time.

Organizational Requirements. The basic concept is that quality control is beyond the boundaries of inspection. Cause rather than effect is the criterion. Naturally, if this concept is to be met, the quality control chief and his major assistants must be equipped personally with schooling in the other phases of the business--engineering and production especially. Furthermore, his organizational set-up must not be in a sort of vacuum, but must integrate very closely with the other groups. Rather than a completely vertical organization, quality control groups are becoming more dispersed, more active, and are evolving liaison relationships. They are getting spotted at critical points so that their service activity may prove to be of value.

As far as administrative practice, this procedure holds. First, get the facts as to degree of uniformity and quality, where it is off, and also cases where it is excellent. Second, have a means to arrive at the cause, using as a thought-provoker, is the trouble due to manpower limitations, process difficulties, product characteristics, financial limitations, market needs, organizational relationships, and so on. The same procedure may be used whether there is a single cause to be isolated or whether a general survey of conditions is to be made. Then having arrived at the cause, third, correct it by enlisting the help of others, securing their cooperation, and holding to the premise of constructive suggestions rather than destructive criticism. Furthermore, do this correction before losses accumulate. Broadly, the effects of such a policy will result in these ends:

1. Increase in pride of craftsmanship.
2. The forcing of management and services into a practical consideration of problems, both administrative and technical.
3. The creation of a stimulating agency for teamwork of all parties concerned.

Excellent quality control can be a major influence in creating a successful enterprise. Why? Well, if a company is making something that a lot of people initially want, it also has to be superbly done to maintain that want.

STATISTICS AND TIME STUDY

Arthur B. Wright
AC Spark Plug Division - General Motors Corp.

Production emphasis today by management and labor groups has placed great weight upon time study and its part in measuring productivity.

Time Study Uses

To perform successfully the duties placed on its shoulders, time study must be as exact as we know how to make it. Its need for great accuracy can be seen because it is the basis for (1) production rates, (2) product and operating costs, (3) determination of labor requirements, (4) equipment and tooling requirements, and (5) efficiency reporting and control.

Time Study Tools

To present an understandable picture to quality control men, a few facts of time study methods must be mentioned.

In establishing operation standards or standards for an operation type, many time studies must be taken with common elements, and stop watch readings must be recorded for these elements and compared. Where extreme accuracy is required, motion pictures are used.

Operation work methods are examined closely with the act breakdown, which serves as a tool to improve and describe the operation.

Time Study Tools and Their Quality Control Equivalents

	Time Study	Quality Control
1.	Operation	Parts
2.	Act Breakdown	Part Print
3.	Stop Watch	Micrometer
4.	Motion Picture Camera	Electric Amplifier Gauges

Statistical Analysis of Time Study Data

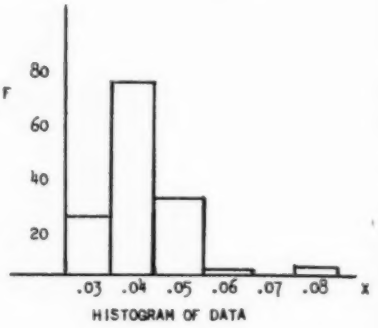
At this point, statistical analysis is required to measure economically the data presented by time study, or to control quality. A time study becomes a sample of the whole day's work on an operation, and a statistical method is used -- that of the average, standard deviation description of the population with a resultant possible error at various probability levels. Possible error can be obtained by either the standard error of the mean at a probability level of .68 or the A. S. T. M. method in their "Presentation of Data" handbook (pp.39-42) at probability levels of .90 or .99.

Statistical Analysis of a Time Study - Sample Calculations

TIME STUDY - GRIND ON ROCKER ARM

X	F	FX	FX^2
.03	28	.84	.0252
.04	78	3.12	.1248
.05	34	1.70	.0850
.06	1	.06	.0036
.07	0	.00	.0000
.08	2	.16	.0128
TOTAL	143	5.88	.2514

$\bar{x} = \frac{5.88}{143} = .041128$



HISTOGRAM OF DATA

$$\sigma = \sqrt{\frac{\Sigma fx^2}{n} - x^2} = \sqrt{\frac{.2514}{143} - .0016915} = \sqrt{.0017580 - .0016915}$$

$\sigma =$ .00814

Permissible Error (5%) = .002056

Possible Error (Sample of 143, $a = \frac{1.645}{\sqrt{143 - 3}}$) at a probability of .90.

$a\sigma = .139\ (.00814) = .001131$ or 2.9% .

Practical Guide in the Range-Average Graph

Because of the amount of work involved in such calculations, it is clearly evident that some simpler method is desirable. This has become possible thru the development of the range-average graph by Dr. A. G. Swanson of the mathematics department of general motors institute, working with the time study department of the division I represent.

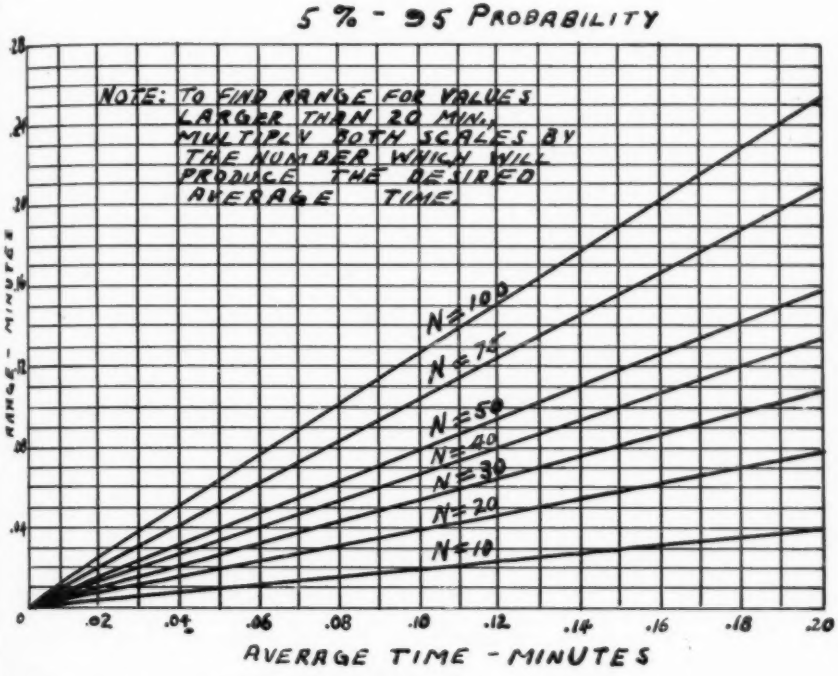
In every time study taken, a range of readings is encountered as well as an average that must be computed. With changes in range, the standard deviation and possible or expected error also change. It is evident also that the greater the size of the sample, the smaller the expected error. Since the average and the range of observations are determined by the operation, a possible or expected error can be set by arbitration, with the sample size taken to fulfil the possible error requirements.

The development is based on the equation

$$K = \frac{R}{\sigma},$$

Where R is the range, K is the average ratio between the range and the standard deviation of a succession of samples, and σ is the standard deviation of the sample taken.

As K and a values* vary with sample sizes, proper substitution for K, a, and $\bar{X}$ will give a range. This has been developed into the following graph for a 5% permissible error and a probability level of .95. The graph clearly shows for a known average or $\bar{X}$ value whether the sample size is sufficient or inadequate with a given range. This graph when attached to the time study man's board shows at a glance the requirements to fulfill a statistical analysis of the time study being recorded.



Machine Rate Losses and Binomial Expansion Predictions†

Machine rates, or where an operator runs more than one machine, have losses due to interference that cannot be measured without great cost. These losses occur when one machine is down with the operator working on it and another machine goes down. With two machines down at the same time, the operator can only work on one, with some resultant loss in machine capacity. The extent of this can be predicted by the binomial expansion. This law of probabilities is a mathematical expression for the total combinations of the chances that given events will occur or not occur. The amount of overlapping machine downtimes can then be computed, using a mathematical formula for the probability law.

* Biometrike, Volume XVII, L. H. C. TIPPETT.
† Factory Management & Maintenance, March, 1941, Bernstien.

For example, in the flipping of coins, the chance for heads or tails is equal, i.e., one-half the time heads should appear, and the other half tails should appear. Thus, with one coin ($\frac{1}{2} + \frac{1}{2}$) = 1 would be the total of the combinations. Flipping two coins at the same time could result in the following combinations:

H - H, T - H, H - T, and T - T.

The binomial distribution expanded for two coins, or $(H + T)^2$, predicts the following: (H is heads and T is tails).

$$(H + T)^2 = H\,H + 2\,T\,H + T\,T,$$

or the same combinations as noted above. Using numerical values in $(H + T)^2$, where the chance for these combinations is one out of two, $(\frac{1}{2} + \frac{1}{2})^2$ gives (1/4 + 2/4 + 1/4).

Just as this law of probabilities can be used to summarize the combinations of coins, so it can also be used to predict the combination of idle machine time and productive machine time with the resultant losses due to interference.

Example of Probability on 5 Spindle Automatics to Determine Machine Loss

The tool changing and stocking allotments indicate that a 20% downtime condition exists over an eight-hour period. Hence, on a one machine rate, the downtime is 20% and the running time is 80%, with a machine utilization of 80%.

For A Two Machine Rate

$$(Q + P)^2 = Q^2 + 2QP + P^2 = 1.00$$

$Q^2 = (.20)^2$ =	.0400	2 machines down together
$2QP = 2 \times (.20)\,(.80)$ =	.3200	1 machine down at a time
$P^2 = (.80)^2$ =	.6400	0 machine down
Total	1.0000	

From these figures, it can be seen that two machines are down together 4% of the time and that one or other of the two machines is down for a total of 32% of the time. This means that the operator is busy 32% with one machine down and 4% on each of two machines when they are down together for a total of 40% downtime on two machines. The loss in production due to one machine waiting for the other is 4%. This divided by the machine rate of two then gives the loss figure in machine efficiency of 2%, or a net machine efficiency of 78%. To clarify this, it simply means that the loss of 4% for two machines occurs when the second machine waits while the first machine is down. A diagram may aid in understanding this. The wait occurs because only one operator is used and as a result the formula must be compensated. If two operators were used, no wait time would be involved.

☐ 4% down (Part of 20%) ☐ 4% down - wait

☐ 4% down (Part of 20%)

☐ 32% of the time 1 machine down

64% - 4% (wait) or 60% no machines down

In a like manner, the development can be made for an operator running three, four, or more machines when the downtime and running time are known.

Machine Utilization

The ideas illustrated above can be developed into chart form for quick reference, which then presents a guide to the losses to be expected on multiple machine rates.

EFFECTIVE MACHINE UTILIZATION

MACHINE RATE	MACHINE DOWNTIME -- PER CENT					
	5	10	15	20	25	30
	EFFECTIVE MACHINE UTILIZATION					
1	95%	90%	85%	80%	75%	70%
2	94.9	89.5	83.9	78	71.9	65.5
3	94.5	89.0	82.8	76	68.8	61.0
4	94.3	88.5	81.8	74	65.6	56.5

Time Study in Acceptance Sampling

Time study standards, based on quality control procedure, can be established knowing inspection time required and the frequency of the inspection. For example suppose lots of 2400 parts are to be handled as follows: 300 parts will be selected at random and checked. If one or more of these are rejected, then an additional 450 pieces will be inspected. If seven or more of the 450 pieces are rejected, then the remainder of the lot must be inspected. Based on the inspection time and the frequencies of the inspect and reinspect, standards can be set on this job with resulting efficiency in controls.

WHY STATISTICAL QUALITY CONTROL GETS RESULTS

Lloyd A. Knowler
State University of Iowa

Probably the most important reason that Quality Control by Statistical Methods has been so successful in business and industry is that it is founded upon sound sceintific principles. The hunches, the whims, the guesswork have been largely eliminated--the initiative is retained; in fact, additional time is left to management and employees for progressive and worth-while reflection as to ways and means to improve the quality of their product or service at an economical level.

Those using the procedures recognize the possibilities (as well as the limitations) inherent in their process which may include men, materials, and machines. They recognize the relationships which exist between each of these elements. They recognize that the behavior of persons varies from time to time, from day to day, from week to week; but what is most important, they recognize that these variations can be measured, charted, and that evaluations can be made based upon them. Hence a sound scientific procedure underlies the decisions.

In a similar manner, they recognize that materials vary from time to time within a plant, from company to company, and from season to season. Again the variation can be measured, charted, and evaluations made.

The combination of the variations because of men and material can also be measured, charted, and evaluated. Those using statistical quality control procedures recognize that the total variation because of men and material is not the sum of the two separate variations--they recognize the extent that one variation tends to "wash out" the variation of the other.

The same conditions hold for machines. In fact, many persons in a shop consider a machine as being comparable to a human being in that variation exists, not only from day to day, but during the day. It is generally known that many machines tend to be somewhat "jumpy" at the beginning of a run. As the machine "warms up", so as to speak, a more uniform product is produced. Again the amount of variation is measured, charted, and accounted for.

As before, the total variation because of men, materials, machines, while greater than any one of the three separate variations, is not as great as the sum of all of them. The tendency for one to "wash out" or annul the effects of the others is discovered. The amount of this reduction is rather well determined.

Occasionally the comment is made that mathematics is too precise a science to be useful in practical applications in that the practical applications have too many variables. In such case, the person fails to realize that in the mathematical profession we often have not only

an infinite number of variables, but we also have an infinite number of variations of each variable. Certainly as many as are ever met in practice.

Elsewhere in this conference we have seen how to determine averages, ranges, and plot the results on a control chart. We have seen that the control chart not only gives a stationary picture of the process, but it also presents a moving picture of the entire operation from the beginning to the end or to any phase of the operation. A study of the control limits as set by the process gives the width of the highway within which the process is capable of operating. We have observed that inconsistent results are obtained where plottings are off the highway. We have seen that when plottings tend to drift one way or the other, trouble will soon occur--that danger is lurking--a most important predictive value. Investigation is started long before trouble occurs. Constructive action is taken. Management suggests critical points in the production line at which control charts are located, and hence the source of trouble can be more quickly localized. The more management and employees use the control charts, the more they like them--additional information is readily available for decisions.

Many of us are interested in short runs--possibly the job shop. We recognize the value of statistical procedures in a long run where a number of similar articles are produced, but how about my situation? It is different! At one time this thought was prevalent in each of the industries which are so successful today. It is not essential that each piece be alike. In fact, we know that no two pieces are ever exactly alike. Applications have been made where no two pieces where intended to be the same. Applications have been made in the production of but one item per week. Applications have been made where only a few items are on one order--such applications are especially valuable if a similar run will be made at a later time. One fact is often overlooked--the control chart on one machine or on one operation is essentially the same as an application in a small concern even though it is a part of a large unit.

Although many of us like to consider the value of control charts in connection with a production line, or in fabrication, we find more and more progressive engineers who make use of statistical quality control in setting specifications and in designing the product. They study the capabilities of the process. Based on factual information, they determine whether it is economical to purchase new machinery or redesign old machinery, to devise a new lay-out or to make minor alterations in the present one. They can select those employees who need further training in an operation. Occasionally, they find that an operation can be entirely eliminated thereby releasing personnel for other functions for which they are needed. In many cases they realize their specifications are set too rigidly; in many others they discover that they are only kidding themselves with their present method of setting specifications.

Another important phase of statistical quality control is that of acceptance sampling. In many plants, the customary procedure is to

examine 10% of the incoming merchandise and base the decision upon examination of the 10% sample. The results of such procedure are often very misleading.

To be specific, we will consider the results of two such sampling plans wherein:

(1) A buyer is willing to accept material which is 3% defective; and

(2) A producer submits material which is $\bar{p}$ defective.

Plan I

Suppose the buyer takes a 10% sample from each lot submitted and accepts the lot if the sample contains 3% defective or less.* (If a lot contains 330 items, then the sample n contains 33, and the acceptance number c is 1.)

In this plan the disposition of the lots submitted will be as follows:

$\bar{p}$	Size of lot 330 n = 33, c = 1		Size of lot 1000 n = 100, c = 3		Size of lot 5000 n = 500, c = 15	
	Proportion of lots		Proportion of lots		Proportion of lots	
	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected
.00	100%	0%	100%	0%	100%	0%*
.01	96%	4%	98%	2%	100%	0%
.02	84%	16%	86%	14%	95%	5%
.03	74%	26%	65%	35%	55%	45%
.04	63%	37%	44%	56%	16%	84%
.05	50%	50%	27%	73%	3%	97%
.06	42%	58%	15%	85%	0%	100%
.07	34%	66%	8%	92%	0%	100%
.08	26%	74%	4%	96%	0%	100%
.09	21%	79%	2%	98%	0%	100%
.10	16%	84%	1%	99%	0%	100%

It is observed that lots containing 330 items at the 3% level will be rejected 26% of the time even though the buyer is willing to accept material at this quality level. In fact, 16% of all lots containing 330 items at the 2% level are rejected--lots which are most desirable. Furthermore, 45% of all lots containing 5,000 items at the 3% level are rejected.

Plan II

Suppose the buyer takes a 10% sample from each lot submitted and accepts the lot if the sample contains no defectives.

In this plan the disposition of lots submitted will be as follows:

	Size of lot = 50, n = 5, c = 0			Size of lot = 100, n = 10, c = 0	
	Proportion of lots			Proportion of lots	
$\bar{p}$	Accepted	Rejected	$\bar{p}$	Accepted	Rejected
.00	100%	0%	.00	100%	0%
.01	99%	1%	.01	92%	8%
.02	92%	8%	.02	82%	18%
.03	86%	14%	.03	74%	26%
.04	82%	18%	.04	66%	34%
.05	77%	23%	.05	61%	39%
.06	74%	26%	.06	55%	45%
.07	70%	30%	.07	50%	50%
.08	66%	34%	.08	45%	55%
.09	64%	36%	.09	41%	59%
.10	61%	39%	.10	36%	64%
.15	46%	54%	.15	23%	77%
.20	36%	64%	.20	14%	86%
.25	28%	72%	.25	8%	92%

It is observed that if each lot has 50 items with 10 defectives (20%) then 36%, over one-third, of the lots will be accepted. A most unfortunate result even though the buyer probably felt certain that he was protected with a 10% sample and no defectives allowed.

This analysis of these plans supports the following points: (1) a large proportion of lots are rejected by Plan I which should have been accepted; (2) a large proportion of lots are accepted by Plan II which should have been rejected; (3) the necessity of taking a large sample if lot quality protection is necessary; and (4) that neither Plan I nor Plan II is satisfactory.

Experience supports the principle that one of the most economical plans for the acceptance of material is that based on a record of control at a satisfactory level--the use of a control chart. Another economical method is to use a standard sampling procedure such as: Sequential Analysis; Army Ordnance Tables; or Dodge-Romig Tables. These procedures are demonstrated elsewhere in this conference.

In this installation of a quality control program, in making the various applications, it is desirable that management understand some of the fundamental principles. Also that the employees feel that they too belong to the unit. Cooperation is necessary--in general, the greator the number of persons who understand the program, the greater the benefits. Statistical quality control based upon sound scientific principles as applied to design, specification, production, and inspection gets results.

APPLICATION OF STATISTICAL QUALITY CONTROL AT MINNEAPOLIS-HONEYWELL REGULATOR COMPANY

S. C. Amren

It is now about one and one-half years since we began using statistical quality control at Minneapolis-Honeywell Regulator Company. We feel that we have made satisfactory progress in improving quality, reducing scrap and re-work, and in cutting production and inspection costs. However, one of the most interesting phases has been in the study of specifications and tolerances. We have found that improper tolerances can be very costly. The most useful statistical tool for the study of tolerances is the $\bar{X}$ and R Chart, and its variations. A thorough knowledge of this tool seems to point to an endless number of uses.

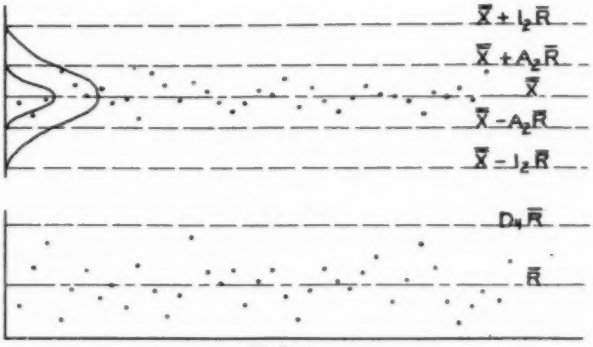


FIG. 1

Figure #1 illustrates a simple X and R chart, indicating that the process from which it was made is in statistical control. The control limits $\bar{\bar{X}} \pm A_2\bar{R}$ give us the extremes of the normal curve for average values. This may also be expressed as $\bar{\bar{X}} \pm 3\sigma_{\bar{X}}$. The $\bar{\bar{X}} \pm I_2\bar{R}$ limits, or $\bar{\bar{X}} \pm 3\sigma_{\bar{\bar{X}}}$, give the extremes of the curve for individual items. By the extremes is meant the 99.73% limits. It is this curve that tells us where we are in respect to our tolerances.

Figure 2A shows the ideal condition. Practically all the individual items are within tolerances. In Figure 2B, we are not as fortunate, and we have the alternatives of either changing the specification or refining the process. In Figure 2C, we find a still more unfortunate situation. Very little product is within tolerance, and if it is possible to shift the process so that its curve will conform to specifications, then that is the step to be taken. In some cases, this may require a major change in the process, which may be quite costly. Should this be the case, it would be well to investigate the possibilities of changing the position of the specification. In Figure 2D, we are too fortunate, as we are not making use of the entire tolerance. Usually, we pay more money for adhering to smaller tolerances, and therefore, it would be well to investigate the possibilities of speeding up the process to a point where we use practically all of the tolerance.

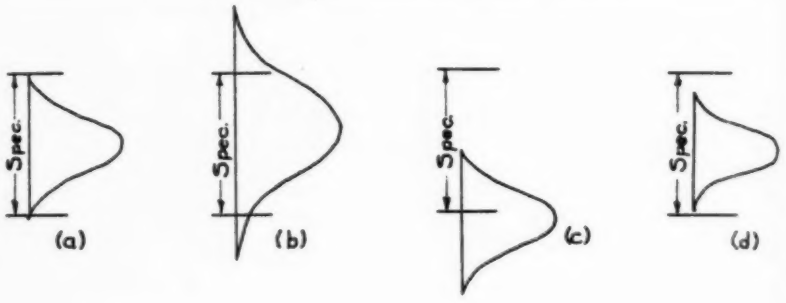


FIG. 2

Some of the problems with which we must deal to meet the specifications successfully leads us to ask a few questions:

1. Is the process capable of producing to the required tolerance?
2. Can we measure accurately enough to determine what the process is doing?
3. Will the article being measured repeat itself?

Obviously, we cannot answer Number 1 until we have answered Number 2 and Number 3. Let us therefore consider Number 2 first.

FIG. 3

If we are to set out to machine a part to a total tolerance of .001" when the only measuring device available is a regular 6" scale, we could hardly hope to be successful, and if we were successful, we wouldn't know it. Even if we had a regular micrometer which could be read to .001", it would still be doubtful if we could do a satisfactory job in the long run. We must accept the fact that all measuring devices have some error, whether it be mechanical or human. If we assume that the error of the measuring device is as much as indicated by the shaded areas in Figure 3A, should we now accept the distance between the shaded areas A and B as our working tolerance, or should it be more, or less? The answer is more, since by examining Figure 3B with the longer curve representing observed values, and the smaller

representing measurement error, we can conclude that the probability of getting an observation at either extreme is quite small, and likewise the probability of getting a large measurement error is quite small. The probability of getting an observation at one of the extremes, and a measuring error at its extreme and in the same direction at the same time, is indeed very small.

We may determine our true values by applying the following formula: $\sigma'_{ov} = \sqrt{(\sigma'_{me})^2 + (\sigma'_{tv})^2}$. Where σ'_{ov} represents the standard deviation of the observed values, σ'_{me} is the standard deviation of the measurement error, and σ'_{tv} is the standard deviation of the true value. The standard deviation of measurement error may be obtained by taking several readings of a constant value with the same measuring device. It is evident from the above formula that the true value is smaller than the measured value, so that measurement error really has the effect of penalizing the production process. In other words, it makes the process look worse than it actually is. It is, therefore, important that measurement error be kept at a minimum. However, there is always a limit beyond which it is inadvisable to go. Usually the more accurate we make a measuring device, the more it is likely to be a laboratory set-up, and unsuitable for production processes. Measuring equipment must be rugged enough to stand the normal abuses of operators and inspectors.

The question now arises: "How accurately should we be able to read our measuring equipment?". We may get some idea if we examine a problem wherein our total tolerance is one gram. In order that our curve for individual items shall coincide with the tolerance of one gram, $\bar{R}$ cannot excede .39 grams. If $\bar{R}$ is .39 grams, the normal curve for individual items will just barely have its 99.73% coinciding with the extremes of the tolerance. Some industries have adopted the scheme of getting the proper increment size for the measuring device by the simple ratio of $\bar{R}/10$. Others say $\bar{R}/20$ is the ideal, and $\bar{R}/10$ is a minimum. If we adopt $\bar{R}/10$ we have .39/10 = .039 as the increment size, and we would then have about 25 increments within a tolerance of one gram. Still other opinions would set 20 increments as the minimum which would be approximately the ratio $\bar{R}/8$. Regardless of which plan we choose, it does seem logical that 20 increments should be a minimum, and probably 60 increments a maximum, and if our measuring device falls within this range, we should not have excessive measurement error.

Let us now consider question Number 3. "The ability of the article being measured to repeat itself." This type of variation, or error, is usually found in assemblies such as switches, relays, etc. Since we manufacture a variety of thermal time switches, we are constantly concerned with this type of variation. Suppose we consider a problem wherein we are to set the switches for a timing of approximately 50 seconds. In a switch of this type, we must recognize that there is bound to be some variation in succeeding operations. If the adjustment is made at 50 seconds, within what limits will it repeat? If we assume that all switches repeat within ± 5 seconds of 50, we could

accept that figure as our tolerance. However, if we desire to make our initial adjustment anywhere between 48 and 52 seconds we would then need a tolerance somewhat in excess of 50 ± 5.

A little more than a year ago, we encountered a problem of this nature in the manufacture of a small snap switch. There were some very critical adjustments, the most difficult being that of trip and return efforts. We had a specification on trip effort of 25 ± 1 grams and return effort 5 ± .75 grams. A good percentage of the switches were consistently being rejected for non-conformance to these tolerances. Measuring equipment seemed quite adequate, but the process universe could not be narrowed down to conform to the existing specifications. We then began running control charts on these adjustments after 100% inspection, and we were quite surprised to see that the universe spread was identical with the chart on the adjusting process. It was then evident that the natural tolerance was ± 2 grams for trip effort, and ± 1.75 grams for return effort, and that no amount of sorting could change the picture. Tolerances were then changed to coincide with the natural tolerance of the switch, with a savings in excess of $100,000 a year in adjusting and inspection costs. Furthermore, life tests indicate that the switch is consistently better now than when we had narrower tolerances. This condition undoubtedly arises from the fact that all adjustments are under statistical control.

It is, therefore, apparent that tolerances can be costly unless properly set, and it should be obvious that the measuring device is just as important as the production process itself. We cannot determine the capabilities of a production process unless we take into account measuring error and repeatability.

SCIENTIFIC CONTROL OF STOCKROOM INVENTORIES

R.H. Wilson
Bell Telephone Laboratories

While a stockroom is probably the oldest form of organized business, it seems to be the one part of modern business which has had the least scientific attention. The reason for this is that the proper economic control of a stockroom is far from the simple thing it appears to be, and in reality is a very complex problem.

This is seen from the fact that while most highly-placed executives are very disturbed about large inventories they discuss them only in general terms, and because of their inability to properly define the problem they have to leave whatever control is exercised to lower executives and clerks.

Elements of Inventory. Obviously what is needed is a clear presentation of the elements which enter into the control of inventories. In order to lead up to this let us first consider the way in which a stockroom inventory is taken. See Exhibit 1.

First of all it is essential to make arrangements to take the inventory over a short space of time so that an accurate picture of the stock on hand at some given time is obtained. The inventory itself is taken by counting the number of units of each stock item on the shelves, multiplying this by the cost of each unit and finally adding the amounts so calculated for all stock items. The total obtained is the dollar value of inventory. From the manner in which this is done it follows that the stockroom inventory is simply the sum of the inventories of all individual stock items in the stockroom. Therefore, in order to get at the heart of the inventory problem, we have to get down to a consideration of the elements which create the inventory of a single stock item.

This brings us to Exhibit 2 which shows the movement of a typical stock item over a period of a few years. Now the thing I want you to notice about this exhibit is that the inventory at any particular time is made up of two parts - one depending upon the quantity of stock ordered and the other part depending upon the quantity of stock left on the shelves when the fresh stock was received. For example, if we take the inventory at a time represented by A (i.e. at the beginning of October 1944) then the amount on hand is obviously influenced by the 1000 units which were received at B as well as by the fact that 90 units were on hand at B when this order was received.

If a great many inventories of any item are taken over a number of years and averaged we would obviously be very close to determining the average amount of stock carried during that time. Therefore, in Exhibit 2, the average amount of stock on hand is indicated as the average inventory. It will be noticed that the two parts into which this is divided are called the active stock and the safety stock. The active stock depends for its size on the activity of the item while the safety stock represents the amount of stock used as a

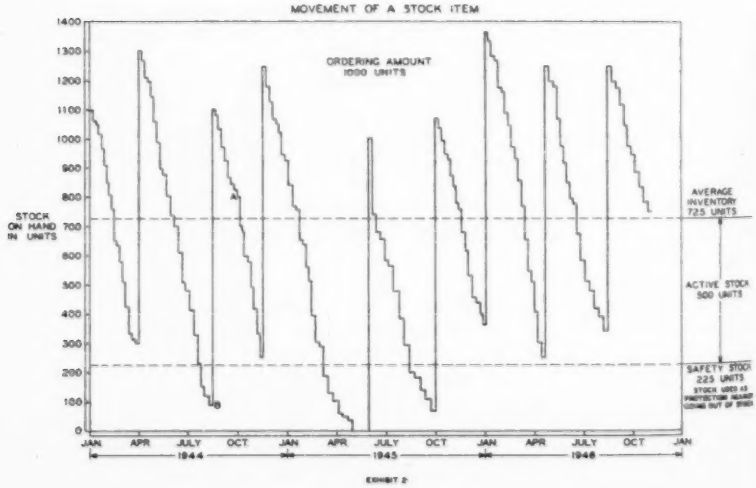
INVENTORY RECORD

DATE 10/16/46

(SHEET NUMBER 1)

(1) STOCK ITEM	(2) NUMBER ON HAND	(3) COST PER UNIT	(2) X (3) INVENTORY
.015 X 36" VARNISHED LINEN	496 YDS	$ .57 YD	$ 282.72
500 WATT FROSTED LAMP	116	.93 EA	107.88
TERMINAL LUG	2492	.03 EA	74.76
1/2 WATT 400,000 OHM RESISTANCE	726	.10 EA	72.60
D-163597 JACK	106	6.50 EA	689.00
GAS LIGHTER	145	.25 EA	36.25
TIGER BRAND LINE	37 BAGS	.60 BAG	22.20
S-304 SOCKET	77	.14 EA	10.78
221G RETARD COIL	62	2.35 EA	145.70
6AK5 VACUUM TUBE	420	2.20 EA	924.00
TUBE SOCKET CINCH	1950	.73 EA	1423.50
9881 SOCKET	825	.11 EA	90.75
COAXIAL JACK	273	.46 EA	125.58
6" CORD	28	.40 EA	11.20
		TOTAL	$4016.92

EXHIBIT I



cushion to prevent the item from going out of stock due to increased demands or long delivery times. The active stock is one-half the average amount ordered, while the safety stock is the average of all the values of stock on hand when fresh stock is received.

Now these two sections of the inventory are based on two entirely different functions of stockkeeping. One function is to buy sufficient stock to meet the overall demand while the other is to see that adequate stock remains on the shelves during the time that fresh stock is on order; both have to be considered when trying to keep the inventory at a minimum.

Consequently it is general practice to set up two control factors for each stock item to take care of these separate functions. The two factors are called by a variety of names; the most common being "maximum stock" and "minimum stock." We call them the "Ordering Amount" and the "Ordering Point." In the plan of operation to be described in this article the Ordering Amount is the most economical amount of stock to purchase, while the Ordering Point is the number of units of stock below which the stock on hand should not be allowed to drop before a repeat order for stock is started. As will be shown later the ordering point value we determine is the minimum for adequate protection against going out of stock. While the Ordering Amount and the Ordering Point have an effect upon each other which influences the inventory, we will consider this later and for the sake of simplicity consider each of these factors separately.

Ordering Amount. There are many reasons why it might be advisable to purchase stock in small amounts. These are:

(a) There is a low investment in stock
(b) There is less insurance required
(c) There is less depreciation and obsolescence
(d) There is a smaller tax to be paid where taxes are assessed against stock
(e) There might be other factors of a similar nature which cost less to carry when small amounts of stock are ordered, such as rent, cleaning, heat, etc. if the stockroom area varies with the amount of stock carried.

On the other hand, there are also a number of valid reasons why it might be desirable to purchase stock in large amounts. This is because when large restocking orders are placed there will be

(f) Fewer stock reorders
(g) Fewer receivables in the Receiving Dept.
(h) Fewer individual inspections of incoming stock
(i) Fewer deliveries to stockrooms
(j) Fewer receivals in stockrooms
(k) Fewer bills to be paid.

It follows therefore from an economic standpoint that there are arguments why restocking orders should be small and why they should be large. The most economical ordering amount obviously lies some-

where in between, and it can be shown mathematically that the variable yearly operating costs due to purchasing different amounts of stock vary with the size of the restocking order as shown in Exhibit 3. It should be noted that the curves in Exhibit 3 will vary considerably for different stockrooms depending upon the values of the above economic factors in each organization but they will all fall into the same general pattern.

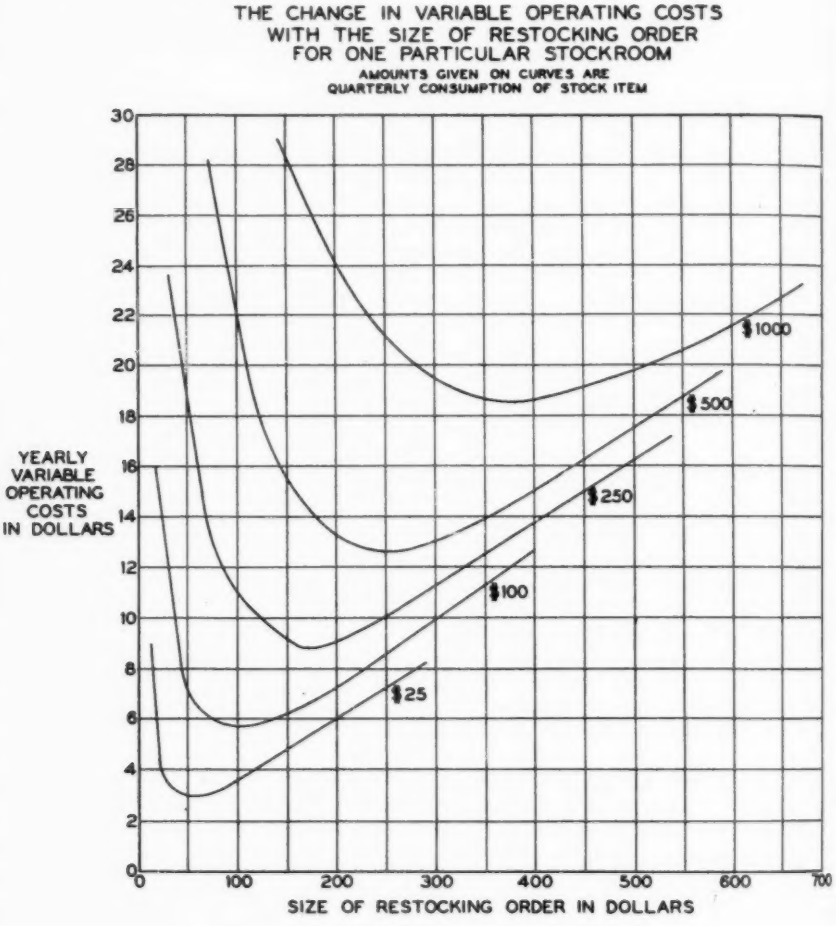


EXHIBIT 3

It is obvious from the exhibit that there is one size of restocking order for each stock item which is definitely the most economical size to purchase. For example, in the stockroom for which Exhibit 3 was prepared $170 worth of stock should be ordered if the quarterly demand is $250. Ordering in lots of $50 would increase the variable yearly operating costs from $9 to $19, or 111%. While this may seem

small in dollars it amounts to a considerable figure if multiplied by all the items in the stockroom.

This example also shows that the inventory should not be the only factor considered in judging the operation of a stockroom, because the inventory is obviously lowered if we order in lots of $50 worth of stock instead of $170 worth, but we see that this can be done only at in increase of 111% in the variable yearly operating costs.

THE CHANGE IN VARIABLE OPERATING COSTS
AS DIFFERENT AMOUNTS OF STOCK ARE ORDERED
FOR ONE PARTICULAR STOCKROOM

AMOUNTS GIVEN ON CURVES ARE
QUARTERLY DEMANDS OF STOCK ITEMS

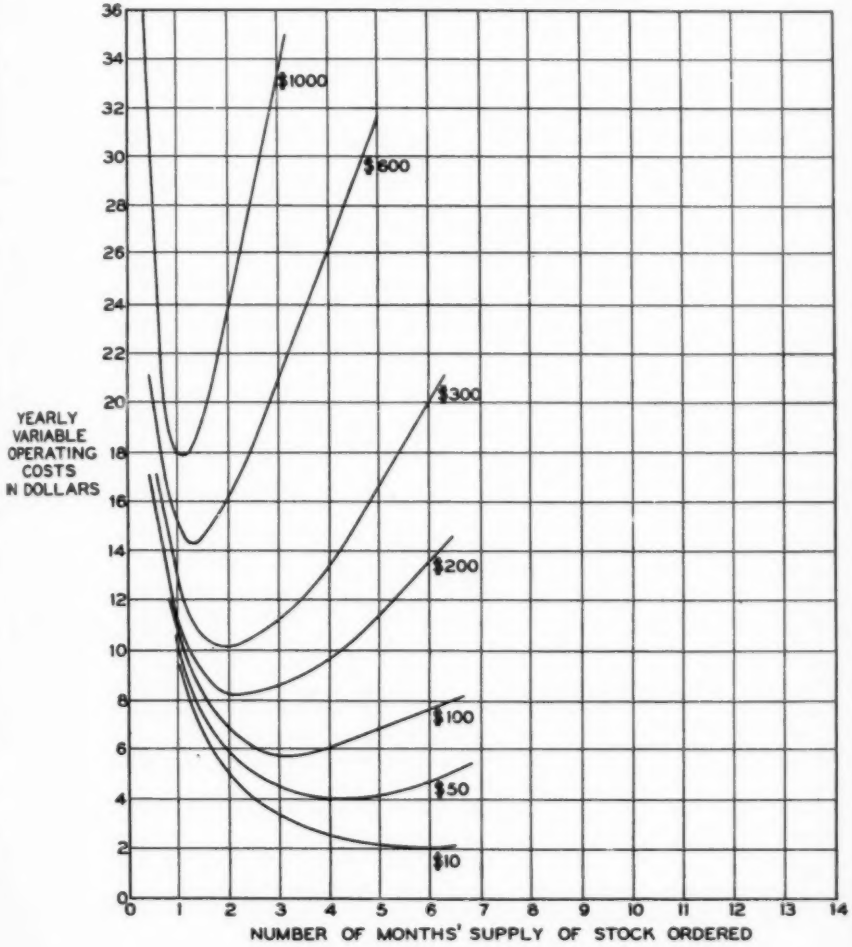


EXHIBIT 4

The same curves are presented in a different way in Exhibit 4. Here the variable yearly operating costs are plotted against the size of the restocking order expressed in the number of months' supply of stock ordered.

This exhibit shows that the practice of purchasing a given number of months' supply for all stock items is very uneconomical. For example, if 3 months' supply of stock is ordered for all items, then this is most economical for the item moving at the rate of $100 per quarter, but for the item moving at the rate of $1000 per quarter the variable yearly operating costs would be $33, whereas they would be reduced to $18 if we purchased one month's supply, a drop of 45%.

It is not necessary to use charts like Exhibits 3 and 4 to order stock. A table can be prepared which provides a much simpler method of operation (see Exhibit 5).

Exhibit 5 is used when a stock item has reached its Ordering Point. At this time an estimate is made of the amount in dollars which will be withdrawn during the next quarter, using past records and any knowledge of future demands. This figure is located in the first column of Exhibit 5 and the Ordering Amount is given on the same line in the adjoining column.

There are a very few cases which require special consideration. If items are put up in standard packages it may be advisable to pick the nearest number of standard packages of the ordering amount given in Exhibit 5. Also should an item be very cheap and bulky or have a short shelf life it might be necessary to order less than the amount specified in Exhibit 5.

Contract Orders. In order to save repetitive orders or to get better terms, it is sometimes advisable to place a contract order for a longer period and specify deliveries as requested. The amount given in Exhibit 5 is then requested when the Ordering Point is reached.

Discounts. Other conditions occasionally arise which introduce additional economic factors that might make it advisable to depart from the Ordering Amounts from Exhibit 5 in order to operate at minimum cost. The most important ones are those which result in a discount in the purchase price or its equivalent. These are where:

(1) Discounts are offered for purchasing in quantity.
(2) Different suppliers have different list prices and offer varying discounts for quantity purchases.
(3) Different suppliers offer various periods within which payment may be made.
(4) Transportation rates per unit of the stock item may be lowered as the amount purchased increases.
(5) Transportation rates may differ where one supplier is located further from the user than another.
(6) Different suppliers offer different discounts for cash payment of bills.

Under (1), (2) and (4) it will be noticed that a discount is offered as an inducement to order in large quantities but if we

ORDERING AMOUNT

QUARTERLY DEMAND DOLLARS	ORDERING AMOUNT DOLLARS	TIME ORDERING AMOUNT WILL LAST
UP TO 6	ORDER ONE YEAR'S SUPPLY	12 MONTHS
7	26	11 "
8	28	10.5 "
90	95	3 MONTHS
100	100	3 "
110	105	3 "
120	110	12 WEEKS
140		"
	670	3.3 WEEKS
3000	740	3.2 "
3400	805	3.1 "
3800	865	3.0 "
4200	925	2.9 "
4600	985	2.8 "
5000	1045	2.7 "

EXHIBIT 5

refer back to Exhibit 3 it will be seen that this will result in increased operating costs. Consequently it is necessary to find whether the discount offered will more than offset this rise in operating costs. This condition lends itself to mathematical treatment and results in tables which indicate immediately whether the discount is large enough to warrant increasing the Ordering Amount (see Exhibit 5-A).

ORDERING AMOUNT AND DISCOUNT TABLE

THE DISCOUNT SECTION IS USED TO DETERMINE WHETHER IT IS ECONOMICAL TO INCREASE A STOCK ORDER TO GET BETTER TERMS OR DISCOUNTS AND PAYMENT PERIODS OR TO SAVE ON TRANSPORTATION CHARGES.

QUARTERLY DEMAND DOLLARS	ORDERING AMOUNT DOLLARS	TIME ORDERING AMOUNT WILL LAST	INCREASE IN SIZE OF ORDER TO GET A DISCOUNT — THIS IS CALCULATED BY DIVIDING THE SIZE OF THE STOCK ORDER IN DOLLARS REQUIRED BY THE SUPPLIER FOR A STATED DISCOUNT BY THE STANDARD ORDERING AMOUNT. THE FIGURES BELOW INDICATE THE SIZE OF DISCOUNT WHICH MUST BE OBTAINED BEFORE IT IS ECONOMICAL TO INCREASE THE ORDERING AMOUNT BY THE AMOUNT INDICATED ABOVE.														
			1.5	2	2.5	3	3.5	4	5	6	7	8	9	10	12	15	17	20	25
UP TO 6	ORDER ONE YEAR SUPPLY	12 MOS.	.6																
7	28	11 "	.6																
8	28	10.5 "	.5	1															
9	30	10 "	.5	1															
10	32	9.5 "	.4	1	2														
12	34	8.5 "	.3	1	2														
14	36	7.5 "	.3	1	2	3													
16	39	7.5 "	.3	1	2	3													
18	42	7 "	.3	.9	2	3	3												
20	44	6.5 "	.3	.8	1	3	3												
25	49	6 "	.3	.8	1	3	3	4											
30	53	5.5 "	.2	.7	1	2	3	4											
40	61	4.5 "	.2	.6	1	2	2	3											
50	68	4 "	.2	.6	.9	2	2	3	4										
60	75	4 "	.2	.5	.8	1	2	3	4										
70	80	3.5 "	.2	.5	.8	1	1	2	3	4									
80	88	3.5 "	.2	.5	.8	1	1	2	3	4	4								
90	95	3 "	.1	.4	.7	1	1	2	3	4	4								
100	100	3 "	.1	.4	.7	1	1	2	3	3	4	4							
110	105	3 "	.1	.4	.7	.9	1	2	3	3	4	4							
120	110	12 WKS.	.1	.4	.7	.9	1	2	2	3	3	4							
140	120	12 "	.1	.4	.6	.9	1	2	2	3	3	4							

NOTE - When comparing two or more orders which carry discounts select the one for which the discount exceeds the figure given in the table by the largest amount.

EXHIBIT 5-A

It will be noticed that the left-hand side of Exhibit 5-A is Exhibit 5 which is used as just described to determine the Ordering Amount.

To use Exhibit 5-A select from the top line the figure representing the number of times the Ordering Amount has to be increased to get the discount and drop down this column to the figure on a line with the Ordering Amount. If this figure is less than the discount, then it is economical to make the larger purchase unless there is much more chance of obsolescence or depreciation. The net discount actually made is the difference between the offered discount and the selected figure from Exhibit 5-A.

For example, if an item is moving at the rate of $100 per quarter, then the ordering amount is $100. But suppose that for a $400 order the supplier will give a 2% discount. Is it profitable to take it? Exhibit 5-A supplies the answer. $400 is 4 times the standard ordering amount of $100, so select the column headed by 4 and drop down this column to the line of the ordering amount where the figure of 2 is found. This means that the increase in operating costs by increasing the standard ordering amount 4 times is the equivalent of a 2% discount, but the discount offered is only 2% so there is

no economical advantage in increasing the order. If a discount of 5% had been offered (and if the item is a staple) then the order could be increased but the effective discount would be 5% - 2% (the 2% from Exhibit 5-A) or 3% and not 5%.

Operating Advantages of the Ordering Amount Table. We now come to a very important point which is that it is not only the simplicity of Exhibit 5 which makes it desirable for ordering stock. Its use also exerts a tremendous effect upon the inventory, turnover, and other aspects of stockroom operation as follows:

Inventory. It will be seen from Exhibit 5 that it is only for items on which the monthly dollar amount disbursed is small that a large number of months' supply of stock is ordered. As soon as the monthly disbursement reaches $ 3,- ($100 quarterly in the table) the amount purchased is 3 months' supply and as the monthly disbursement increases over this $33 figure the number of months' supply purchased decreases for economical operation. As a result, the overall inventory is, in general, kept at a low figure.

Obsolescence. Another advantage of this routine method of operation is that as the demand for an item decreases, the amount reordered automatically decreases so that there is very much less chance of carrying items for which there is no demand or which have become obsolete.

Turnover. By following this method of restocking, each item is handled so that its overall operating expense is at a minimum; consequently it operates at its best value of turnover. Therefore, the turnover of the stockroom as a whole for all the items is also most economical.

This completes the present discussion of the Ordering Amount and we will now consider the Ordering Point which is the second controlling factor in stockroom management.

Ordering Point. In order to understand the elements which determine the size of the ordering point, refer to Exhibit 6 which illustrates the movement of a typical stock item.

The original ordering point was set at 420 units so when stock dropped to this amount at A a restocking order for 1080 units was originated. This order was received at A' when the stock had dropped to 122 units.

Later in 1945 when stock again dropped to 420 units at B another restocking order for 1080 units was started. However, the demand increased causing the item to run out of stock before this order was filled at B'.

As a result the ordering point was increased to 670 units and a restocking order started at C. This resulted in the order being filled at C', when there were 225 units on the shelf.

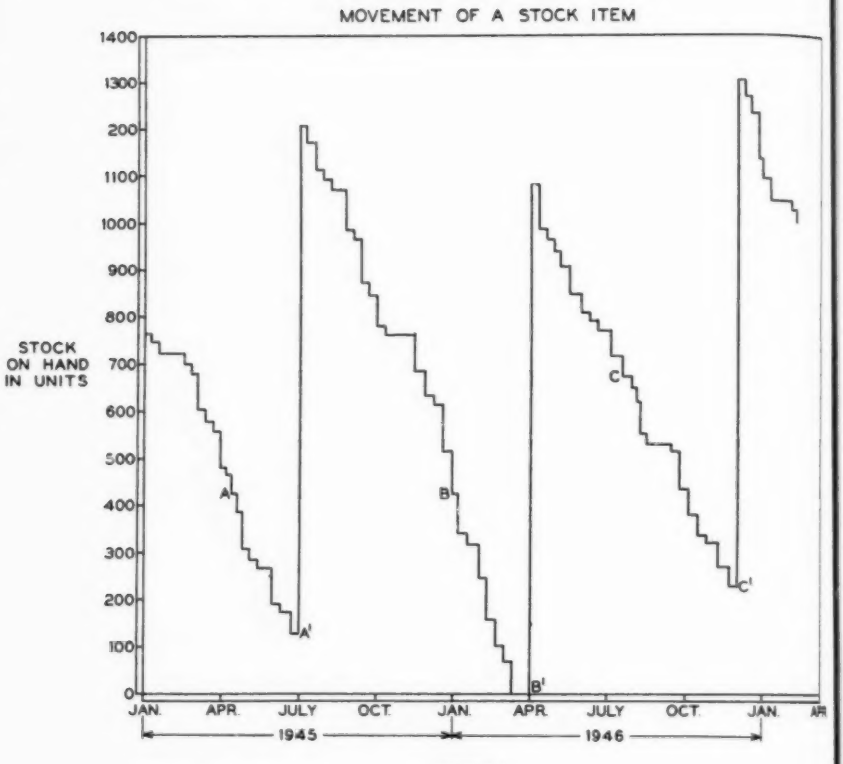


EXHIBIT 6

Obviously for good operation the stockroom does not want to be out of stock; however, if the ordering point is set too high and stock comes in while there is a large supply on hand then the inventory is unduly inflated.

What is needed is the smallest size of ordering point which will maintain the inventory at a low level, yet will keep the number of times out of stock so low that it will be acceptable as good service. Of course, it would be ideal to have no out-of-stock condition at all and this can be managed, but only at the cost of carrying a very large inventory; an inventory much too big from a practical standpoint. It can, however, be applied to a few stock items, important enough to justify the expense of complete protection.

The reason why it is so difficult to prevent an item from going out of stock is that while stock is on order there are three conditions which might arise to cause the supply on hand to be depleted before the fresh supply arrives. These are:

PROBABILITY TABLE FOR AN AVERAGE OF 17 REQUESTS PER DAY

NUMBER OF REQUESTS PER DAY	NUMBER OF DAYS IN YEAR ON WHICH NUMBER OF REQUESTS IS THAT GIVEN IN FIRST COLUMN
2	(1 DAY IN 534 YEARS)
3	(1 DAY IN 94 YEARS)
4	(1 DAY IN 22 YEARS)
5	(1 DAY IN 6-1/2 YEARS)
6	(1 DAY IN 2 YEARS)
7	1
8	2
9	4
10	7
11	11
12	15
13	20
14	25
15	28
16	30
AVERAGE 17	30
18	28
19	25
20	22
21	17
22	13
23	10
24	7
25	5
26	3
27	2
28	1
29	(1 DAY IN 1-1/2 YEARS)
30	(1 DAY IN 2-1/2 YEARS)
31	(1 DAY IN 5 YEARS)
32	(1 DAY IN 9 YEARS)
33	(1 DAY IN 18 YEARS)
34	(1 DAY IN 33 YEARS)
35	(1 DAY IN 68 YEARS)

EXHIBIT 7

1. The number of customers (requisitions received) using the item can be above average.
2. They can ask on the average for amounts larger than they have been doing.
3. It can take longer than expected to get the fresh supply of stock.

When the demand comes from many sources the number of customers requesting an item will vary in accordance with the law of probability. This is the law which tells you your chances of holding four aces when playing bridge, or two pairs when playing poker, or confirms the fact, which you already know, that the more often you toss a penny the greater your chances are of getting as many heads as tails.

When applied to the number of customers asking for a stock item the law of probability indicates that if there are 17 customers per day, on the average, then we can expect over a long period of time that demands will be received as indicated in Exhibit 7. This shows that the average number of 17 can be expected only on 30 days in the year while other numbers can be expected as indicated in the exhibit. There is one other very important part of this law which is that there is no reason at all why over a short period of time the number of customers should average out. In other words, during the time it takes to restock we can just as readily expect that the number of customers will be more than average as less than average.

To further complicate the situation the number of customers asking for the item has no direct connection with the amount each customer requests. While we might get fewer customers during the restocking time, they might readily ask for more units of stock than has been the custom in the past; while a larger than average number of customers might ask for less. What might also happen is that a greater than average number of customers might withdraw a greater than average amount of stock, thus making a bad situation worse.

Furthermore, the number of units requested per customer does not follow a very simple law. This is indicated in Exhibit 8 which is an example of the variations which usually occur in the number of units requested. From it we see that more customers ask for 1 unit (or 1 set) than ask for 2 units; more ask for 2 than for 3; more ask for 3 than for 4 and so on, with a slight deviation from this for half a dozen and a dozen. This type of demand is said to follow an exponential law.

Meanwhile during 1946 we have experienced the worst period we have ever had for obtaining stock. The general shortage of material has given us values of restocking times which vary for one item from a few days to more than a year. For this reason, restocking times have become a very important factor in determining ordering points.

TYPICAL EXAMPLE OF THE NUMBER OF UNITS PER REQUISITION FOR A STOCK ITEM.

NUMBER OF UNITS DRAWN OUT PER REQUISITION	NUMBER OF REQUISITIONS
1	174
2	98
3	56
4	49
5	25
6	33
7	12
8	13
9	8
10	7
11	3
12	5
13	2
14	2
15	1

EXHIBIT 8

Because of its complexity, combining as it does the law of probability, an exponential function, and a widely varying value of restocking time, the computation of the Ordering Point resolves itself into a mathematical study.

Although the original mathematics was done many years ago when conditions were more regular, we have been using the results of the study to set ordering points and control the out-of-stock condition under varying circumstances since 1935. Under actual operating conditions we predict in advance the out-of-stock condition we can accept as good service, (bearing in mind the fact that to do better than this will increase the inventory more than is justified). The stock control clerks then use simple tables developed from the study to set ordering points which will give the degree of service specified by management.

Up until 1940 we were able to predict in advance the out-of-stock condition to within a very small percentage. During the war years, however, the demand for materials principally on war contracts rose from $440,000 per year to as much as $1,440,000 as shown in Exhibit 9. At the same time the type of work changed continually as hundreds of different war contracts were completed and it also became

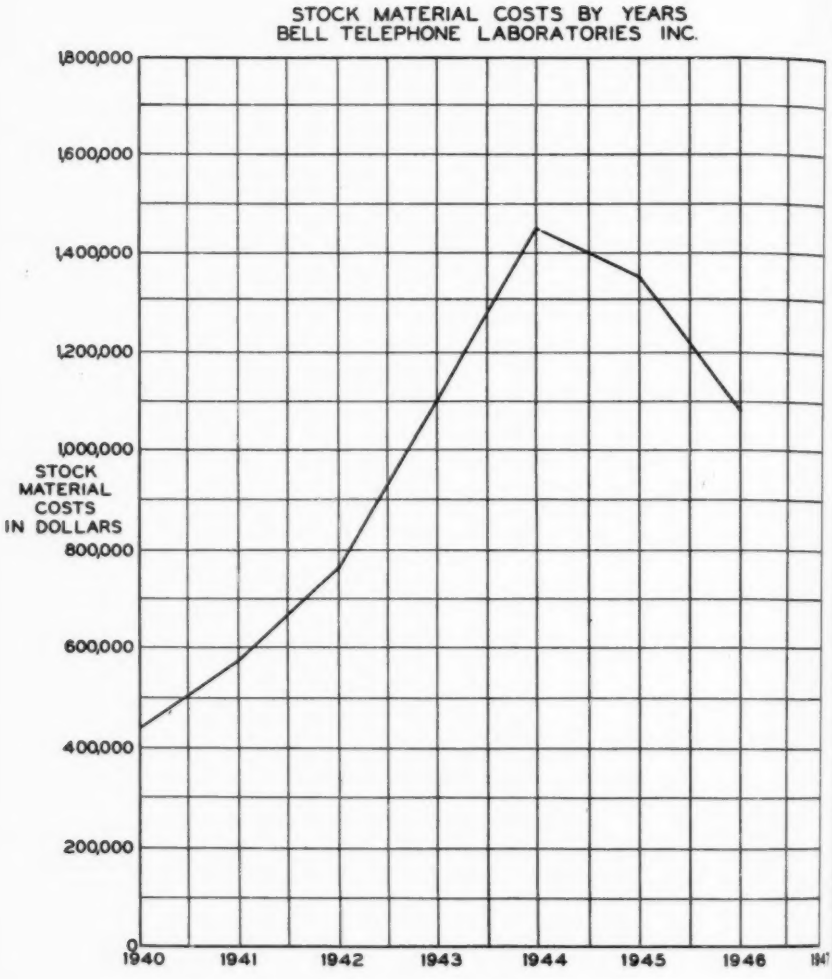


EXHIBIT 9

progressively more difficult to get deliveries of stock. This gave our method of control an extremely severe test. However, we continued to use the routine method of setting ordering points and found that we could still control the out-of-stock condition with remarkable accuracy. This is shown in Exhibit 10. As far as I know, no contract failed to meet its scheduled date for lack of stock material.

Before considering the kind of table used to set ordering points there are two effects mentioned earlier in this article which should be considered.

AVERAGE NUMBER OF STOCK ITEMS CARRIED
COMPARED WITH ACTUAL AND PREDICTED NUMBER
OUT-OF-STOCK AT ANY ONE TIME

THE PREDICTED OUT-OF-STOCK CONDITION
WAS LOWERED IN SEPTEMBER 1942

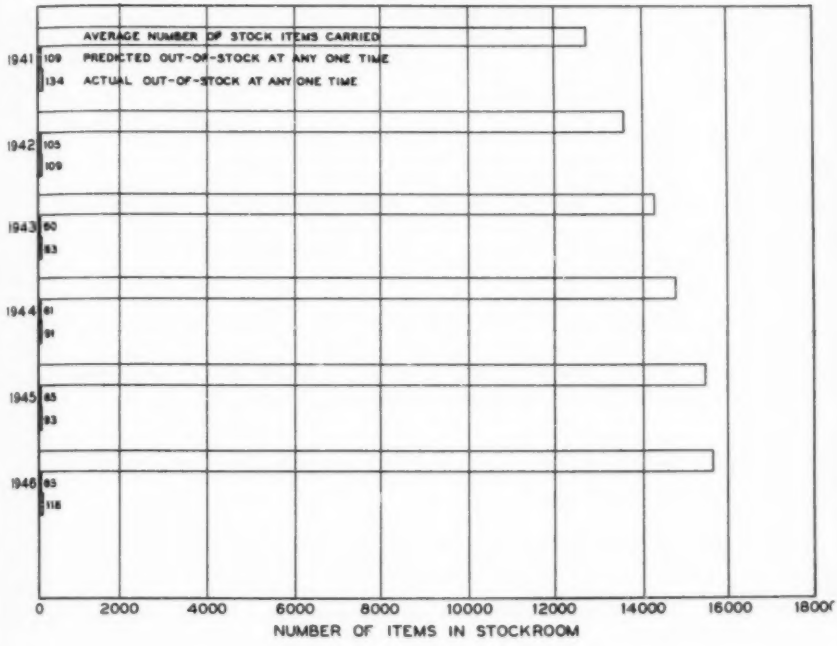


EXHIBIT 10

Effect of the Ordering Point on the Ordering Amount. As previously pointed out, Exhibit 2 shows that the inventory is made up of two components; the active stock depending upon the size of the Ordering Amount and the safety stock depending upon the size of the Ordering Point. Since there is never any actual division into these two components, management is never aware of the part each plays and is only conscious of the overall inventory figure. However, when mathematics is applied to find the most economical size of ordering amount both components have to be considered, and if the safety stock is large it has the effect of increasing the size of the ordering amount for most economical operation.

Large restocking times result in larger values of a safety stock. This, in turn, because of the effect noted above, increases Ordering Amounts and consequently Inventories.

From a practical standpoint, this effect, together with all the other economic factors, is taken care of in the preparation of the Ordering Amount Table (Exhibit 5), so that no additional effort is required on the part of the stock control clerks.

Effect of the Ordering Amount on the Ordering Point. The size of the Ordering Amount naturally affects the Ordering Point. If we buy

10 years' supply of an item we won't need to worry about its Ordering Point for the next ten years. If we buy one years's supply then we can't possibly go out of stock more than once a year; if we buy 6 months' stock we can't possibly go out of stock more than twice a year and so on. This is all taken into account in the simple tables which have been developed to determine the size of ordering points necessary to obtain any desired degree of protection against going out of stock.

Ordering Point Tables. Ordering Point Tables can be prepared for any out-of-stock condition from once out of stock every other time a restocking order is placed to never out of stock, but it should be kept definitely in mind that an increase in protection is reflected in an increase in inventory. The Ordering Point in any case is the minimum number of units which will give the desired degree of protection.

Exhibit 11 is one ordering point table which insures that the item will not run out of stock more than once in 5 years. Tables can be prepared for 1 year, 2 years, 10 years, 20 years or any other degree of protection, and they all operate under the same instruction.

To use Exhibit 11 the average number of requisitions which will be received during the maximum restocking time is first calculated from past records of a stock item.

This figure is then found in the first column of Exhibit 11 and to the right along the same line and under the appropriate column for the time the Ordering Amount will last (from Exhibit 5) is found the number of requisitions of average size which have to be covered by the Ordering Point.

If this figure is multiplied by the average number of units withdrawn per requisition, the Ordering Point is obtained in its usual form as so many units of the item.

Self-Manufactured Items for Stock. A further mathematical study has resulted in tables which can be used in a routine way to determine the most economical lot size to manufacture for stock provided the basic manufacturing cost and the setup cost are known for the stock item under consideration.

General Application. The elements of inventory control which have been discussed in this paper are basic to all kinds of stock carried in any stockroom. The mathematical study was not limited to any specific type of material or to any economic factors in the stockroom. Therefore, the plan of operation is generally applicable.

Records. One other important point is that in introducing this plan there is no need to change the records now in use in any organization provided they give a record of the movement of each item and the restocking times. The simplicity of the needed record and the speed with which ordering amounts and ordering points are calculated also keeps the number of clerks at a minimum.

ORDERING POINTS

USING THESE VALUES, AN ITEM WILL RUN OUT OF STOCK ON AN AVERAGE OF ONCE EVERY 5 YEARS. TO OBTAIN THE ORDERING POINT, MULTIPLY THE NUMBER SELECTED BELOW BY THE AVERAGE NUMBER OF UNITS DRAWN OUT PER REQUISITION.

AVERAGE NUMBER OF REQUISITIONS DURING NORMAL MAXIMUM RESTOCKING TIME	LENGTH OF TIME STOCK ORDERED WILL LAST																				
	WEEKS												MONTHS							YEARS	
	1	2	3	4	5	6	7	8	9	10	11	12	3	4	5	6	8	10	12	1-1/2	2
.2	4.1	3.2	2.8	2.5	2.3	2.2	2.0	1.9	1.8	1.7	1.5	1.4	1.3	1.1	.9	.6	.1	-	-	-	-
.5	5.9	4.7	4.3	4.0	3.8	3.6	3.4	3.2	3.1	3	2.8	2.7	2.5	2.2	2	1.8	1.5	1.2	.9	.3	-
1.0	7.7	6.6	6.1	5.6	5.3	5	4.8	4.6	4.4	4.3	4.1	4	3.9	3.5	3.2	2.9	2.5	2.2	1.9	1.2	.3
2	10	9.2	8.5	7.9	7.6	7.3	7.0	6.7	6.5	6.3	6.1	6	5.9	5.4	5	4.6	4.2	3.8	3.4	2.5	1.9
3	12	11	11	9.8	9.5	9.2	8.9	8.6	8.4	8.2	8	7.8	7.7	7.2	6.7	6.2	5.7	5.2	4.7	3.8	3.1
4	14	13	12	12	11	11	11	10	10	9.9	9.7	9.5	9.4	8.8	8.2	7.7	7.1	6.5	6.	5	4.2
5	16	15	14	13	13	13	12	12	12	12	11	11	11	10	9.7	9.1	8.5	7.9	7.4	6.2	5.3
6	18	17	16	15	15	14	14	14	13	13	13	13	13	12	11	11	9.9	9.3	8.7	7.4	6.4
7	20	18	17	17	16	16	15	15	15	15	14	14	14	13	13	12	11	11	9.9	8.5	7.5
8	21	20	18	18	18	17	17	17	16	16	16	16	15	15	14	13	13	12	11	9.7	8.5
9	23	21	20	20	19	19	18	18	18	17	17	17	17	16	15	15	14	13	12	11	9.6
10	24	23	22	21	21	20	20	19	19	19	19	18	18	17	17	16	15	14	14	12	11
12	27	26	25	24	23	23	23	22	22	22	21	21	21	20	19	19	18	17	16	14	13
14	31	29	28	27	26	26	25	25	25	24	24	24	24	23	22	21	20	19	18	17	15
16	33	32	31	30	29	29	28	28	27	27	27	26	26	25	24	23	22	22	21	19	17
18	37	35	34	33	32	31	31	30	30	30	29	29	29	27	26	26	25	24	23	21	19
20	40	38	36	35	35	34	33	33	33	32	32	31	31	30	29	28	27	26	25	23	21
30	53	51	50	48	48	47	46	46	45	45	44	44	43	42	41	40	39	38	37	34	32
40	67	64	62	61	60	59	58	58	57	57	56	56	55	54	53	51	50	49	47	45	42
50	79	77	75	73	72	71	70	69	69	68	68	67	67	65	64	63	61	60	58	55	52
60	92	89	87	85	84	83	82	81	80	80	79	79	78	77	75	74	72	71	69	66	63
70	105	101	99	96	95	94	93	92	92	91	90	90	89	88	86	85	83	81	80	76	73
80	117	113	110	108	107	106	105	104	103	102	102	101	101	99	98	96	94	92	91	87	83
90	130	125	122	119	118	117	116	115	114	114	113	112	112	110	109	107	106	103	101	97	93
100	142	137	134	131	130	128	127	126	126	125	124	124	123	121	120	118	116	114	112	108	104
120	166	160	157	154	152	151	150	149	148	147	147	146	145	143	141	140	137	135	133	129	124
140	190	183	180	176	175	173	172	171	170	169	169	168	167	165	163	161	158	157	154	149	144
160	213	206	202	199	197	195	194	193	192	191	191	190	189	186	184	182	179	177	175	169	164
180	236	229	225	221	219	217	216	215	214	213	212	211	210	207	205	203	200	198	196	190	
200	258	252	247	244	242	240	238	237	236	235	234	233	232	229		222	219	217			
300	372	364	358	354	351	349	347	345	344	343	341	340	339								
400	485	476	469	464	460	456	453	451	450	448	447										
500	597	586	578	573	568	563	560	558	556	555	553										
600	708	697	687	681	675	671	667	665													
700	819	807	796	789	782	777	772														
800	929	917	905	897	889	883															
900	1039	1026	1014	1006																	
1000	1149	1135	1124																		

EXHIBIT II

Forecast of Benefits. If an organization has been maintaining stock records for each stock item on which are recorded the number of requisitions received, the number of units withdrawn on these requisitions and the time taken to replenish stock, then it is possible without distrubing present operation to pretest a small percentage of these at random which will indicate:

1. The decrease in inventory under the plan described in this article for different out-of-stock conditions which can then be related to the current out-of-stock condition,and

2. The number of stock reorders in a year compared with the current number.

This information will indicate definitely the benefits to be obtained by this scientific plan of inventory control.

Conclusion. A scientific study of stockroom management, lasting over a period of many years, has made it possible to describe in detail the relationship between the economic and service aspects of stockroom operation.

The information already given has shown that the inventory is only one of three main factors in operating a stockroom; the others being the cost of replenishing stock (i.e. purchasing, receiving, distributing, and bill-paying) and the out-of-stock condition. The overall cost of operation depends on all these three factors. Consequently, in general, it is not the lowest possible inventory that is most desirable but that value of inventory which will provide material as needed at the lowest overall operating cost.

As a result of the study, it is now possible for management to provide ordinary clerks with simple tables and instructions by means of which the inventory and the out-of-stock condition can be definitely controlled. By this is meant that when using this plan of operation a prediction can be made in advance as to what effect a drop in inventory will have on the out-of-stock condition and the overall operating costs. Conversely if the out-of-stock condition is not satisfactory, management can be informed in advance just what rise in the inventory figure and in operating costs can be expected if better service is desired. Meanwhile management can be assured that the operating costs so obtained are the lowest possible for the service rendered.

As a final statement it can be said from past experience that management, in exercising control of its inventories under this scientific plan, can expect two very important results. These are:

1. A material drop in inventory and in the out-of-stock condition when the plan is initially installed and

2. After installation a satisfactory out-of-stock condition and an inventory as low as possible regardless of changing business conditions.

THE APPLICATION OF STATISTICAL QUALITY CONTROL TO THE CONTROL OF WASTE AND THE MEASURE OF PERSONNEL EFFICIENCY

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Statistical quality control was introduced at the Minnesota Mining and Manufacturing Company in the summer of 1945. $\bar{X}$, R, and p chart applications were made in various fabricating departments with economical results. The most recent applications of the Shewhart theory are those made directly to the control of waste and to the measure of production personnel efficiency. It is these recent applications that we will discuss.

This paper assumes familiarity with the $\bar{X}$, R, and p Shewhart Control Chart formulation and technique. It will also refer to the significance of the coefficient of correlation, assuming a basic understanding of this concept.

Application to Waste Control. The Waste Control Superintendent at the Minnesota Mining and Manufacturing Company had been in sympathy with the statistical control program at the plant since its inception. However, no attempt had been made to make application of these concepts in the Waste Control Department. He was anxious that his department derive such benefits as were possible from this new tool of industry, and asked that we attend one of the periodic Waste Report Meetings and study the subject matter from a statistical control viewpoint.

We did attend this meeting and extracted a portion of the report for statistical study. The excerpt was typical of many items in the report, and read as follows: "Process A has 1% Waste", and "Process B has 1% Waste". Inasmuch as process A & B had identical percentages of waste and this percentage was at an apparent economical level, management had accepted this finding as conclusive and satisfactory without further qualification.

In making a statistical preview of this excerpt, we found the phrase "1% Waste" used without a qualifying reference as to average, maximum, or minimum values. Investigating this statement further we found that the phrase "1% Waste" was considered as an average value. We also found no mention made of process variability. Applying the principles of industrial statistical control to our reasonings, we could not concur with conclusions reached from average values without knowledge of the dispersion of the frequency distributions of the universe.

In order that we might unveil the inherent capabilities of Process A and Process B, we obtained sufficient data from each process to compute average, upper and lower control limits for process level, upper and lower control limits for variability, using $\bar{\bar{X}} \pm A_2\bar{R}$, $D_3\bar{R}$, and $D_4\bar{R}$ formulas, and upper and lower control limit values for individuals, using the formula $\bar{\bar{X}} \pm A_2\bar{R}\sqrt{n}$. These values are plotted and identified in Figure 1. This chart also shows a value at the 3.0% level which is

identified as "Specification for Process A and Process B individuals". This was the maximum allowable waste percentage for both processes which had been arbitrarily set from experience and without knowledge of the standard deviation of a constant cause system. Definite instructions accompanying this traditional 3.0% value were briefly as follows: All values exceeding 3.0% were considered anomalous, and an investigation was ordered. If corrective measures were not forthcoming within a reasonable length of time, shutdowns and/or disciplinary action was taken.

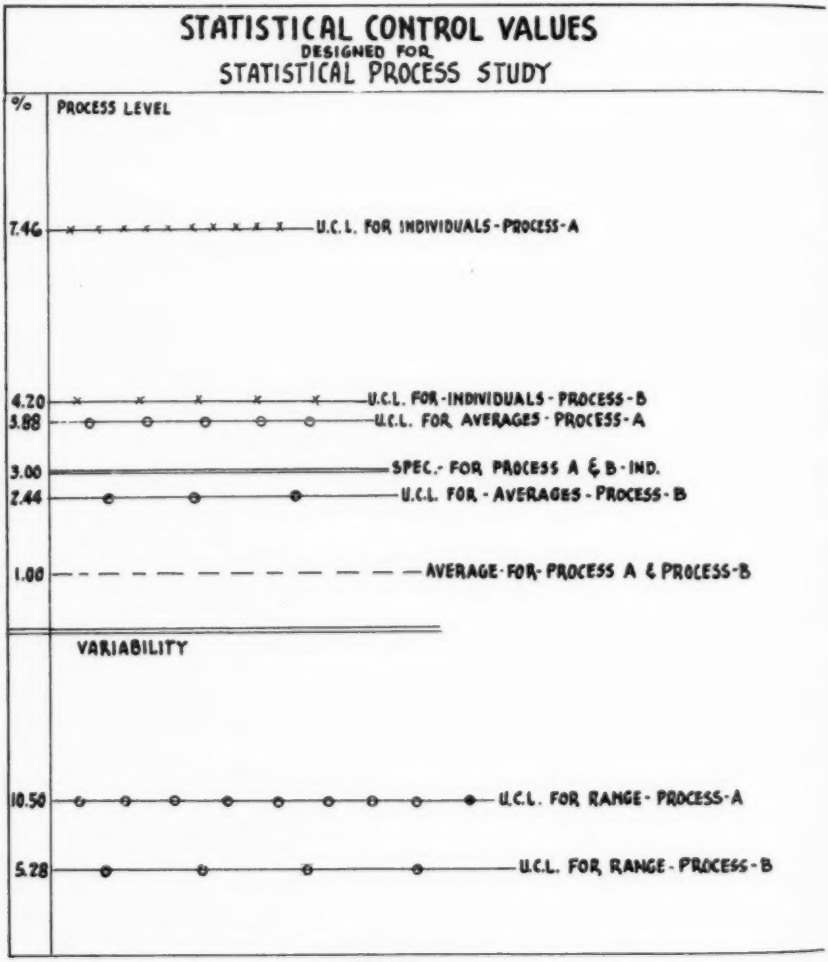

FIG. I

Making a statistical study of the values shown in Figure 1 we found that:

I. Process A & B had identical averages of 1.0% (this was in agreement with the reported Waste Control findings). However, these

processes had substantially different variabilities, and we concluded that Process A and Process B would have different capabilities and would not economically conform to the same specification.

II. All individual values occuring between 3.00% and 4.20% were within the capabilities of Process B but outside the maximum specification limit of 3.0%. All individual values occuring between 3.00% and 7.46% were within the capabilities of Process A but outside the maximum specification limit of 3.0%.

In accordance with the instructions accompanying the 3.0% value all individual values between 3.0% and 7.46% should lead to shutdown orders and/or disciplinary action. Again basing our inferences on the laws of probability distribution, we found that this type of action would be most uneconomical. Unless fundamentals of the processes were changed, we could expect a recurrence of these values, inasmuch as they are inherent to their respective processes. Expensive shutdown and/or disturbing personnel discipline could be of no value.

If the 3.0% specification limit for individuals must be maintained, then we must change the fundamentals of Process A and Process B so as to decrease the average and/or variability in order that the individual process values be brought within the 3.0% limit. If this procedure is not economically practical, then 100% inspection of the process is necessary or a change in the specification standard.

III. With the statistical control values of process level for averages and variability to guide us, we were able to identify a statistically controlled process, thereby passing economical judgment on the uniformity, consistency, and predictability of the waste characteristic.

IV. Because of the significant correlation between questionable or border-line quality and high waste values, it was found to be economically sound from a customer acceptance risk, to identify and, if possible, eliminate high variabilities in a process, regardless of average or specification.

As a result of the above statistical investigation, the fallacy of drawing inferences from only average and arbitrary specification values was clearly proved, and talk in generalities ceased to be of interest in the Waste Control Department. Because of the high probability of erroneous conclusions being drawn from arbitrary specifications, all such waste specifications.were withdrawn and replaced with process statistical control upper and lower control limits,inasmuch as these values did represent the capabilities of the process. However, if in using sound engineering judgment, these capabilities appeared abnormally high, then operators, machines, and materials were studied for some fundamental change toward waste improvement. If and when trends developed and were apparently stabilized, then new statistical control limits were computed and became new specifications limits.

The findings of the above statistical study were of such value that the Waste Control Superintendent asked for factual, objective, and

statistical inferences on all repetitive Waste Control problems. At the present time Shewhart Control Charts are portraying the capabilities of the waste characteristic at many repetitive processing and sub-processing stations throughout the plant. Knowing the factual capabilities of waste at the various processing stations has been of great value to the scheduling, cost accounting, and purchasing departments.

Application of Waste Control Charts to a Multiple Processed Product. In the preparation of statistical waste control charts, historical values were obtained from previous data. These data must be obtained from a process that is repetitive and with the same fundamentals as those being investigated. The formulas $\bar{X} \pm A_2\bar{R}$, $D_3\bar{R}$, and $D_4\bar{R}$ were evaluated, using group size n = 4. Current data were then assembled and detailed on a work sheet. A typical facsimile is shown in Table 1.

FORM 1286

TABLE - 1

STATISTICAL-DATA-WORK-SHEET

TAPE-DEPARTMENT

DEPT A
TYPE 34-60
SUB-PROCESS
1 2 3 4

CODE-ANALYSIS

(a) Raw Backing Sq. Yds. Input
(b) Treated Backing Sq. Yds. Output
*(c) Backing Loss/1M Sq. Yds. Processed
(d) Priming Sq. Yds. Input
(e) Gallons Primer Consumed
(f) Gallons Primer Consumed Per 1M Sq. Yds Primed
(g) Adhesive Sq. Yds. Input
(h) Gallons Adhesive Consumed
(j) Gallons Adhesive Consumed Per 1M Sq. Yds. Coated
**(k) Group Average Range & Identity

*Move Decimal One Place to Left = %.
**These Values Plotted On Shewhart Control Chart

IDENITY	SUBPROCESS-1				SUBPROCESS-2				SUBPROCESS-3			
	(a)	(b)	(c)*	(k)**	(d)	(e)	(f)	(K)**	(g)	(h)	(j)	(k)**
7003-B-4	4836	4728	22.0	GR.-12	4728	65	13.8	GR-12	4728	140	29.7	GR-2
7003-B-5	3974	3849	21.0	Aver.	3849	71	18.3	Aver.	3849	135	34.7	Ave
7003-C-1	4382	4298	19.2	21.5	4298	65	15.2	15.5	4298	148	34.6	32
7003-C-2	4764	4650	23.8	Range	4650	68	14.6	Range	4650	152	32.6	Ran
				4.2				4.5				5.0

Four consecutive values were given an average value, range value, and a group identity. These average values and range values are plotted on the control chart (representing this process) with group identification. If and when a group value, assignable cause, needs investigation, complete identity of individuals may be obtained by referring to the correlating group number on a work sheet, similar to Table 1.

Figure 2 shows an example of a series of control charts which represent the statistical waste control of a product that has multiple processing. Each individual chart in this series represents the statistical waste control of a process or sub-process of the product. In this series of charts a group originating in Department A retains its identity on the same vertical line thru each of the processing or sub-processing stations. A highly comprehensive statistical pattern of waste values for each process and sub-process, and for the process as a whole, is readily discernible.

FORM 896
TAPE

STATISTICAL CONTROL CHARTS

CHARACTERISTIC - WASTE
TYPE - 3M-86

CODE ANALYSIS

DEPT. A
SEC. I SQ.YDS.- LOSS IN TREATING 1M-SQ.YDS.
SEC. II PRIMER CONSUMPTION 1M-SQ.YDS.
SEC. III ADHESIVE CONSUMPTION 1M-SQ.YDS.

DEPT. B
SQ.YDS.-LOSS IN SLITTING - 1M - SQ. YDS.

DEPT. C
SQ.YDS.-LOSS IN PACKING - 1M- SQ. YDS.

COLOR CODE - GREEN - SPECIFICATION - RED-PROCESS

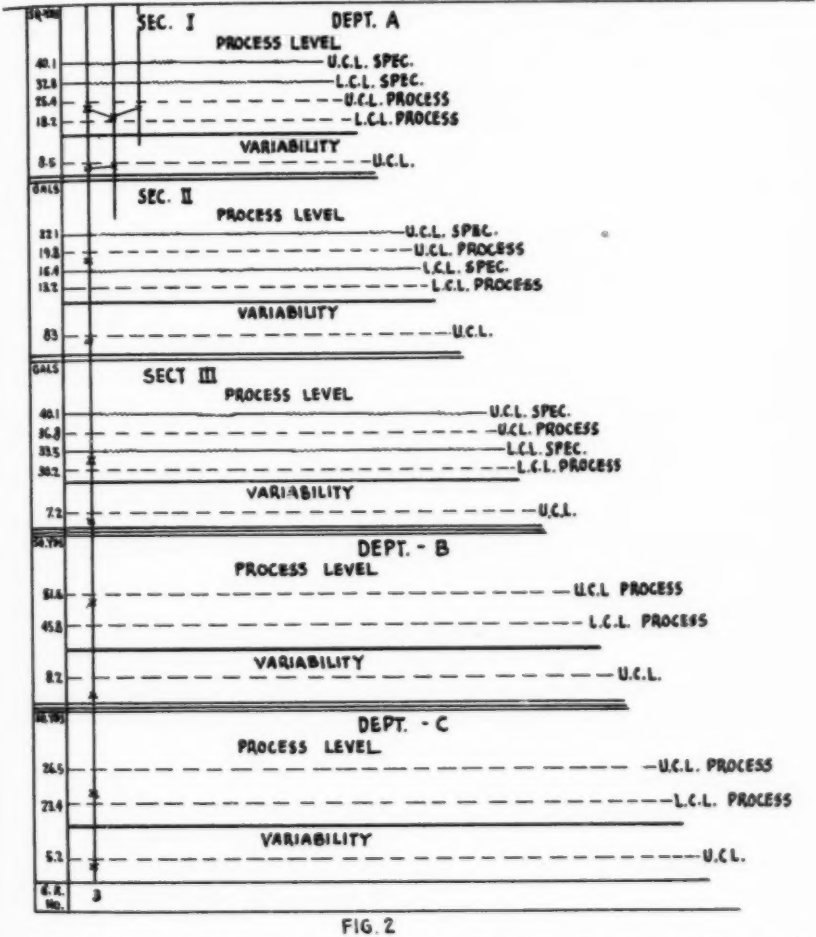

FIG. 2

Application to Personnel Efficiency. Through the cooperation of the Tape Packing Superintendent, we had been able to install our first statistical control charts at the Minnesota Mining and Manufacturing Company. These charts were fraction defective, p charts on reject rolls at the packing table, and reject rolls at the shipping table (Outgoing Quality).

A correlative study of the two variable (1) percent rejects at the packing table and (2) percent rejects at the shipping table, revealed a degree of association that was significant. Further investigation of this subject disclosed the fact that the packing operators were also packing inspectors. We also found these operators working on a production bonus incentive plan which was based on "units packed per unit time".

Because of the variability in percent of rejects in lots received at the packing table and the incentive to maintain percent of bonus earned, a correlation study was made of the variables (1) units packed per hour, (2) percent of rejects at the packing, and (3) percent of rejects at shipping table.

We refuted the hypothesis "The apparent relationship is due to chance", and found a significant correlation.

While working on these correlations we conceived the idea of portraying statistically on a Shewhart Control Chart the capabilities of a REPETITIVE packing process having the same FUNDAMENTALS, using the characteristic "units packed per unit hour". Accordingly, sufficient previous data of the characteristic "units packed per unit time" were obtained for a process. These data were arranged in groups of four, the average and range of the group was taken, formulas $\bar{\bar{X}} \pm A_2\bar{R}$, $D_3\bar{R}$, and $D_4\bar{R}$ were used, and statistical control concepts applied.

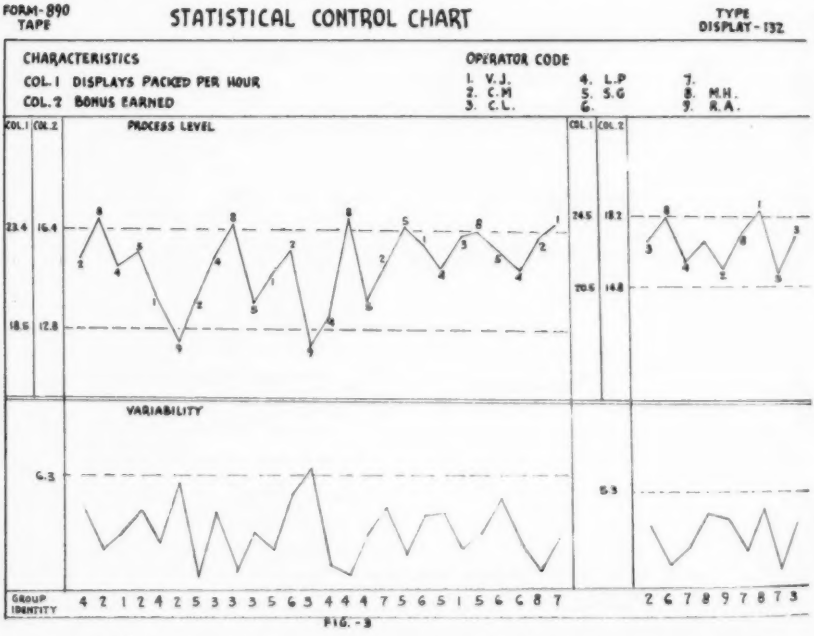

FIG. - 3

Figure 3 is a replica of a portion of an original personnel efficiency chart. This chart reveals the statistical control capabilities

of the characteristic "Displays Packed Per Hour". Each value on the chart represents the average (process level chart) and the range (variability chart) of a group of four values obtained from the same operator, who is identified by a coded numeral. This value is identified by a group number and details concerning the group may be obtained for individual values from a correlating work sheet.

Further reference to Figure 3 reveals two sets of ordinate values on the vertical axis. The values in the left hand column represent "displays packed per hour", the right hand column of values represents "percentage bonus earned".

This chart was originally designed to convey statistical capabilities for only the "displays packed per hour" characteristic. However, because of the monetary appeal to an operator of the expression "bonus earned", we did incorporate the equivalent "bonus earned" value opposite "displays packed".

As soon as the capabilities of this process had been determined and the values determining this capability plotted, the foremen called a meeting of operators connected with this process. The control chart or "news reel" of the operation was discussed. The operators had occasion to evaluate their operations relative to each other and to the process capabilities. Inasmuch as the bonus earned individually is the average earned for the process, each operator's work reflected on the earnings of the other. Attention was called to the variation, in the bonus earned, between operators #8 and #9. Further investigation disclosed the fact that #9 operator was not qualified for this work, and he was transferred.

The trend shown in Figure 3 developed as the result of the meeting mentioned above. Many values went out of the upper control limit. This trend of values became stabilized at a new level, and new control values, as shown in Figure 3, were computed. The new process level values disclosed a substantial increase in production, or bonus earned. The process was now operating in statistical control and with less variability.

We suspected that this increase in production might affect outgoing quality. Accordingly, a further correlation study was made of variables (1) units packed per hour and (2) percent rejects in outgoing quality, and we found the same previous significance existing. We also found the statistical outgoing quality level had not been increased.

A knowledge of the factual process capability of the quantity of production of a process has been of great value to many departments. This knowledge has been used to good advantage in the time study of the process relative to evaluating bonus factors; it has been most beneficial to the scheduling, cost accounting, and purchasing department. Knowing the standard deviation of a repetitive process relative to QUANTITY of production has provided production supervision with knowledge of what the process IS doing and what it can normally be expected to do. This knowledge, as noted in Figure 3, particularly when associated with a bonus plan, has increased quantity without affecting quality.

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SAMPLING METHODS

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Anheuser-Busch, Inc.

Exactness to a degree of infinite detail is the accepted custom in most well organized laboratories. Chemical, physical, and biological analyses are conducted only by most approved methods, which before being applied at all have in most cases first been carefully developed, repeatedly checked, and finally approved by such recognized organizations as the American Society for Testing Materials, the American Association of Official Agricultural Chemists, and many trade organizations or Government Bureaus. Usually, only graduate chemists or analysts working under chemist's supervision expertly apply such methods, and generally strive to employ only apparatus of ever increasing accuracy. To further guard their methods, it is becoming the practice for laboratories to employ standard samples as checks and to periodically compare their results with one another, such as is done when one is a member of the American Society of Brewing Chemists or the American Association of Feed Control Officials.

All this refinement of technique is of little avail, however, if the sample on which the analyst spends hours of time is taken without this same utmost care or without the understanding of the fundamentals involved. It is with the thought of encouraging greater care in sampling that the present consideration of sampling methods is reviewed. For certainly, whenever a quality control group makes a statistical study of test results, the status of the samples must have been considered of unquestionable accuracy. Often times too little sampling or too few samples are taken, or it may be felt that proper sampling may be too expensive. Taking samples from ten per cent of all the bags in every car of barley will certainly be more expensive than just filling a mason jar with some of the barley from a few of the sacks. Or, if a boat load of grain is received and it is found that many sources are represented, the shipment should be broken into lots representing each producer, and separate sampling made of each lot as in the case of the carloads. For analysis these can, of course, be combined and reduced to laboratory size by quartering or mechanical divider. The main point to observe, however, is to sample sufficiently, for, as will be shown in the following pages, the final analysis however accurately made will be no better than the sample itself.

That the method of taking test samples of some types of materials might well become a case for argument can be vividly illustrated by the following example arranged by Dr. Toulouse of the Owens-Illinois Glass Company.[1] An artificial sample is prepared of yellow and red beads, all of uniform shape and weight. These are placed in a box and well mixed. In a particular case, forty red beads were mixed with 960 yellow, making a total of a thousand beads of which 4% were red, or "defective". A paddle having fifty depressions into which the beads may rest is used as the sample scoop. The following table modified slightly from Dr. Toulouse's paper illustrates the results of such chance or random sampling.

TABLE NO. 1

Results of random sampling, by 50's, of a sample containing 4% red beads, 96% yellow beads.

Sample No.	No. of red beads in sample	Sample No.	No. of red beads in sample	Sample No.	No. of red beads in sample
1	1	9	1	17	3
2	5	10	2	18	1
3	2	11	1	19	4
4	1	12	0	20	2
5	2	13	3	Total red beads	41
6	2	14	1	Total beads sampled	1000
7	4	15	0		
8	3	16	3	Fraction red beads	.041
				or	4.1%

Table 1 shows the results for 20 such samples. Inspection of the results shows a fair number of 2's, or the 4% values, but also such extreme variations as 0 and 5. The final average is not the 4% red beads actually in the box. The result obtained by sampling is not necessarily the true value - it may be larger or smaller than the true value, the variation depending both on chance, on the nature of the product, and on the conditions of sampling. If sampling had stopped at the 12th sample, the average value of 4% red would have been obtained; if at the 18th sample, the answer would have been 3.9%; at the 16th sample, 3.6%; if stopped at the 14th sample, the net result would again have been exactly 4.0%. Had the second sample only been used, we would have considered 10% red beads present, while the 12th sample alone indicated no red beads in the box at all. If only the 7th and 8th samples had been taken, one would say that the box contained 7% red beads; the 11th and 12th samples together would have indicated only 1% red beads. Thus, even when we know the true proportion of red beads, random sampling will lead us to mistakes in judgment unless we realize that variations occur, and accept a limit of variation as an acceptability range. Moreover, this experiment represents an artificial mixture with only one variable or difference. All other possible influences or factors are absent except those of pure chance. Still, instances of sampling occur which show as high as 100% uniformity, that is, no red beads, to the other extreme of as much as 10% red beads or 2½ times the actual or true value of 4%. Obviously, such random single sampling, even from a uniform mixture like the above, might result in extremely misleading conclusions.

Dr. Toulouse in a further table compares the number of red beads found in each sample with what could be expected by the law of probability, or as he presents it, by Poisson's distribution values for the conditions established. A modification of his table follows.

TABLE NO. 2

Summary of sampling by 50's in a sample containing 4% red beads, sampled 20 times and compared with Poisson's distribution for these conditions.

No. of red beads in sample of 50	Frequency of red beads	Fraction of red beads	Poisson's distribution values
0	2	.10	.1299
1	6	.30	.2706
2	5	.25	.2762
3	4	.20	.1842
4	2	.10	.0902
5	1	.05	.0346
6	0	0	.0108
7	0	0	.0028
8	0	0	.0006
9	0	0	.0001

Results like the above certainly emphasize the danger of taking too few samples or too small a sample. According to the results in the last column of Table 2, the correct value of 4% red beads should not happen more than 27% of the time, while zero red beads might happen 13% of the time. Zero red beads actually occurred 10% of the time and the correct value of 4% was found in 25% of the samples taken. Samples should, therefore, be large enough and taken often enough to smooth out such variations.

In commercial practice sampling may, of course, assume many modifications. The materials may range all the way from hard flinty substances such as stone, metals, glass, etc., through less hard solids such as wood, paper, cloth, vegetable substances which may further graduate from solids through semi-solid pasty materials down to liquids, and then finally to gases such as carbon dioxide, air, and vapors. All of these require their individual special technique. We may have the simple uniform product such as a liquid which day after day remains the same and offers no variables of any kind. Such might be the ocean water flowing into the open salt drying basins along both sea coasts. I have been told the composition of the sea water rarely changes, so this should give few, if any, problems of sampling. Opposed to this, however, one may consider the many variations and consequent sampling problems introduced by the use of individual containers.

In our own industry the sampling of such containers is one type of quality control which is ever present. Such materials as bottles, cans, cartons, crowns, barrels, etc., arrive in carload lots containing thousands of individual pieces all ostensibly and apparently alike, but actually individual in many ways, with probably no two really identical in every detail.

Amber bottles, for example, may show numerous variables extending all the way from such major factors as interval capacity, shape and dimensions, resistance to breakage, color and composition, to such incidentals as the exact angle of curvature at any point on the shoulder or neck. Still for our own purpose, i.e., to function properly in our bottling lines, bottles must be sampled and tested intelligently and accurately. We have given this matter much consideration, and we attempt regular examination of bottles by such accepted methods as the thermal shock test, hydrostatic pressure, and cutting into sections for measuring wall thickness. These are extremely time consuming and destroy the bottles. Hence, we do not consider it economically feasible to regularly sample and test all lots of bottles by the above tests. Rather than this we have resorted to a regulated control production test which consists of passing a rather large sample through the usual filling process and observing breakage, first in the cases as the bottles arrive, and then in each piece of equipment. Our samples for this test consist of from 288 to 1440 bottles, usually 1% to 2% of the load, selected from various parts of the shipment, either car or truck, as it is unloaded.

As the sample lots of bottles are filled and pass along the line, they are examined also for leakers, principally check cracks on the crown finish, and for color and general shape. If in running the first smaller sample, the breakage is low and the other factors normal, then the shipment is accepted. If above a value considered over our range of acceptability, a second sample twice as large is run in like manner. If the sum of this larger sample and of the first lot averages within our acceptability range, the lot is passed. In this work we strive to follow the acceptance numbers adpted from Ordnance Sampling Tables.

In our examination of bottles, we limit our tests to some three or four major defects. When one considers, however, that in the production of bottles possibly ten chemical ingredients are used including sand and soda ash, all of which no doubt often vary in composition at least slightly, and this coupled with the fact that when the bottles are blown the usual bottle making machines contain nearly three dozen double molds, each of which also may vary slightly, and then finally that the heat of the lehr can conceivably vary and affect the congealing of the ware, the probability of defects in the bottles is greatly increased. In a bulletin of the Hartford Empire Company the possible faults of glassware are listed to a sum of 45 different types of defects. Many of these, of course, may be quite incidental, but any one flaring up to an unusual extent might constitute a sampling problem. Another bottle examination program lists 11 fatal defects and 8 blemishes making the ware subject to possible rejection.

Keeping in mind the extremes found in the example of colored beads as reviewed earlier in this paper where only a single variable was present, one can well expect rather wide variations in the case of bottle samples where sometimes several variables operate at the same time. In the examples listed in Table 3 from actual bottle sampling, we find instances where, on retesting, a higher or lower breakage value is found.

TABLE NO. 3

Breakage Tests on Bottles

Times Sampled	Size of Sample	Bottles Broken	% Broken
1	720 bottles	8	1.1%
2	1440	8	0.6%
Total	2160	16	0.7% ave.
1	720	6	0.8%
2	1440	18	1.25%
Total	2160	24	1.1% ave.
1	720	6	0.8%
2	720	11	1.5
3	1440	24	1.7
Total	2880	43	1.5% ave.
1	720	9	1.2%
2	1440	8	0.6
Total	2160	17	0.8% ave.
1	288	5	1.7%
2	576	6	1.2
Total	864	11	1.3% ave.
1	240	2	0.8%
2	480	0	0
Total	720	2	0.3% ave.
1	288	1	0.3%
1	336	0	0
1	384	2	0.5
1	720	3	0.4
1	384	4	1.0
1	288	0	0
1	576	1	0.2
1	720	4	0.5
1	720	5	0.6
1	720	1	0.1
1	288	4	1.4%
2	576	1	0.2
Total	864	5	0.6% ave.
1	288	5	1.7
2	576	6	1.2
Total	864	11	1.3% ave.

The data in Table 3 show some variation between results but when one recalls the many variables involved they can be considered in quite close agreement. As these results are compared with some previously selected limits, acceptance and rejection can easily be established. In general, the above sampling suffices as a routine control, but for more complete evaluation other attributes must be observed and specific sampling for these carried on, usually by selection of smaller lots of samples from the larger ones used in the above. This insures a good distribution for such selected tests as the bursting test and so on.

Cartons for shipment of the filled bottled beer are received in knocked down form in bundles. When cars of these arrive, one bundle from every 100 bundles is set aside as the car is unloaded. As the sampling of each carload of bundles is completed, further reduction in the number of cartons in the sample has to be made by a type of "Quartering", which consists of removing one or two cartons from each bundle at various parts of the bundle so as to note the effect of position in bundle and pile. Before testing the sample, cartons are conditioned as regards temperature and humidity by placing at a temperature of 70°F and 50% relative humidity for 20 hours. The cartons are then subjected to the various usual tests such as Mullen, G.E. Puncture and Stiffness, Tear Test, weight, thickness, type of paper, moisture, corrugation, values, and so on.

In one carload, the Mullen Test was found to vary from 200 to 230 pounds per sq. inch on one carton, 220 to 250 on another, with a final average for 24 results of 234 lbs. per sq. inch Mullen. In the same lot of samples, the Puncture Test varied from 200 inch-ounces per inch of tear to 220 with an average of 208 for 16 results, while the Stiffness test ranged from 100 to 115 inch-ounces per inch of tear, with an average of 105 for 16 tests.

Sometimes the above tests show considerably wider variation for the several cartons comprising a sample, but when one reflects for a moment on the many variables capable of entering into the construction of corrugated board and its fabrication into cartons, such variables can well be considered possible. For any particular use certain values must be selected for each of the carton tests as the acceptability minimum. In addition to such tests as the above, some of the cartons are selected after making up into finished cartons for additional tests such as the conbur test, drop test, compression test, and regular service tests.

In the case of barrels which are high in value, each shipment is first screened to separate out all packages considered fully satisfactory in every regard. The others are then individually examined for defects, and rejections made if necessary. In addition, one to two per cent of all barrels are set aside as the car is unloaded. These constitute the sample for use in making such tests as shape, weight, volume, dimensions, etc. Punch out discs of the metal are used for chemical analysis, Rockwell hardness, and gauge thickness.

In the sampling of grain shipments, as mentioned earlier, it is customary to sample by probe from 10% of the bags, or in the case of bulk shipments, to use the long grain samplers from five different parts of the car. The official grain sampling tube for bulk samples is divided into ten separate compartments so that a sample from ten layers of the load can be separately inspected by opening the sampling tube onto a large canvas. These samples, often amounting to several pounds, are well mixed and quartered or passed through a mechanical divider, like the Boerner Divider, six or seven times until reduced to one pound or less. This type of divider is equipped with several passages so arranged that by each passing through the divider one-half of the grain is run off to one side.

For mixing or further reduction of the laboratory sample, stirring in the sample jar by means of a rod or spatula should never be attempted. This tends to induce further demixing of the fines. Tumbling in a partially filled jar several times or the use of a large sheet of soft rubber is the best. This permits the grain to be rolled from one side to the other during mixing or if needed for quartering and reduction of sample size. This type of rubber sheet is often more satisfactory for all quartering of some grain samples than the mechanical divider, since we have noticed that whenever fine grain particles are present in a sample they may tend to lodge in the passages of the sampler and escape removal by brushing.

Brewers grains, distiller's grains, and alfalfa meal, for example, should always be mixed on a rubber sheet or other smooth surface prior to removing sample for analysis since it tends to demix on standing. This product contains fines, which are high in protein, and husk particles considerably larger in size. Failure to properly mix such a grain product will certainly result in erroneous analysis. This is also true of a shipment in bags or bulk of any type of grain having fine and coarser particles. The fines tend to go to the bottom, and it becomes almost impossible to sample such a shipment properly unless the whole load is mixed by re-elevation a number of times.

With most types of grain, the weighing out of the actual analysis sample should likewise be carefully done. Usually it is wise to weigh out around fifty grams of the product and have this entire sample ground to a fine mesh powder. From this fine ground sample the further actual test lots can be weighed out.

To further establish the importance of using a large enough sample, an experiment was recently conducted in which we prepared a mixture of two types of rice, both ten mesh broken rice. The mixture consisted of 5% by weight of partially cooked rice which was slightly brown in color, together with 95% of pure white rice. These were well mixed and various size samples weighed out. The two colors of rice were then separated by hand picking and their distribution in each sample determined by weight. Table 4 represents the results of several samplings of the above mixture using various size quantities.

TABLE NO. 4
Sampling of a Mixture of
Rice containing 5% Brown
Rice and 95% Ordinary Rice

Sample Size	Quantity of Brown Rice Recovered	
50 gms.	2.114 gms.	4.2%
	2.995	6.0
	Ave. 2.554	5.1%
25 gms.	1.280	5.12
	1.405	5.60
	1.140	4.56
	0.976	3.90
	1.306	5.22
	1.155	4.62
	1.521	6.09
	Ave. 1.255	5.02% Ave.

TABLE NO. 4 - Continued
Sampling of a Mixture of
Rice containing 5% Brown
Rice and 95% Ordinary Rice

Sample Size		Quantity of Brown Rice	Recovered
5 gms.		0.20	4.0%
		0.28	5.6
		0.35	7.0
		0.20	4.0
		0.27	5.4
	Ave.	.275	5.5%
1 gm.		0.046	4.6%
		0.066	6.6
		0.092	9.2
		0.042	4.2
		0.029	2.9
		0.129	12.9
		0.057	5.7
	Ave.	0.066	6.6% Ave.

The variations in these results are quite similar to those of the bead experiment reviewed earlier in the paper. Even with the individual 50 gram samples a 20% error is noted, but this averages out almost correctly by combining the two samples. In the case of the 25 gram samples, wide variations are apparent but these also even out on multiple sampling. Greater variations appear in the 5 gram samplings, with erratic distributions in the case of the 1% weighings. If a mixture like the above contained one type of kernel higher in some constituent, such as oil or protein, it would be easy to realize what effect such single samples might have on the analysis figures. Proper original sampling of the shipment, thorough mixing, and accurate reduction of the larger sample to the laboratory size, and finally proper mixing and sampling for analysis are just as important as accurate and skillful analysis of the sample in the laboratory.

In sampling hops which come compressed into large bales it is customary to sample ten per cent of the bales by cutting approximately 4" slices of the hops from two sides of the bale and resewing cut burlap wrappings. This method preserves the hop cones for physical examination. Another method for sampling hops is to use a tube-like sampler which because of the sharpened edge can be bored into the bale at the seam. A plunger in the sampler is used to push the hop sample out of the tube. This plunger draws the sample from deeper into the bale and avoids the odor from the burlap wrappings. The hop samples should each be placed in tin cans with friction or screw type covers and closed tightly. For physucal examination spread about 50 to 75 grams on a paper. For chemical examination grind the above quantity in a suitable food chopper discarding first 5 or 10 grams and mixing thoroughly the remainder. Because of the presence of some leaves, stems, and seeds together with the hop flowers, great care should be taken in sampling, and several analysis made for accuracy. When a shipment arrives an effort should be made to sample different lots separately.

For sampling sugars use about 10% of the bags selected from different parts of the shipment or, if over 100 bags, select samples from approximately the square root of the number of bags in the shipment. Where sugar is lumpy and not uniform in size, select lumps of average size and representative of each bag. For fine sugar remove one pound sample with a scoop from well below the surface of the sugar in each bag. Place each sample in a tight container to avoid moisture pick-up. Large slabs of sugar can be sampled by drilling with an auger and collecting samples as above. For combining samples from one lot, spread out on a heavy paper, break up lumps with a hammer, and quarter down to about one or two pounds.

Syrups are sampled by use of a 3/4" diameter tube long enough to reach to the bottom of drums. Prior to sampling, each drum or barrel must be turned over end-wise to mix thoroughly. Ten per cent of the drums should be sampled. For bulk shipments of syrup, sample from spout at intervals during discharge, or draw a sample from the car by means of a sampling "thief". Syrups and lumpy sugars offer some difficulty in sampling due to the viscous nature of the syrup and possible segregation of the sugar in congealing into solids.

For sampling of a bottled or canned product like bottled beer, it is customary to select random samples from the lines at various points depending on the purpose of inspection. For example, to check on the thoroughness of bottle washing, bottles from each rinsing spindle must be separately inspected. These are marked, often plugged with sterile cotton, and brought to the laboratory. To check on the filling height or quantity of beer in the individual bottles, samples must be removed from one complete round of the filler and each filling spout indicated on the bottles. To check application of crowns, samples from each crowner head (6 to 10) must be taken. To check on pasteurization and for analysis of the contents, samples are usually taken at regular periodic intervals from finished production. For sampling the beer from tanks which are under carbon dioxide pressure two methods may be used, either by use of a narrow bore (1/8" I.D.) coiled tube as a resistance to reduce outflow into sample bottles, or by applying a slight back pressure to the bottle prior to sampling. This method can also be used for sampling from draught packages.

The preceding discussion represents some of the more general sampling methods of the brewing industry with which I am at present associated. A number of years ago I was in the dairy industry where sampling of dairy products constituted an important item of consideration. Since these methods differ somewhat, I should like to touch briefly on some of them in the following.

Milk and cream as delivered in 5 or 10 gallon cans by the farmers is first either thoroughly stirred with a disc and rod stirrer or dumped from one can to another several times to remix any cream which usually rises to the surface. A sample is then drawn by means of a 24" long 1/4" tube or by means of a small 1/2 oz. or 1 oz. dipper. Each farmer's samples are placed in one sample bottle. To prevent spoilage of the sample prior to analysis a preservative such as mercuric chloride is used. Frozen cream from storage must either first be thawed out at 40°F or cans placed in 85°F water.

For ice cream mix, sampling is the same as for heavy cream, but for frozen ice cream, a sample is obtained by first removing some of the upper surface and transferring the sample by spoon from the freshly exposed surface into a rubber stoppered sample bottle which should be filled almost full.

Sampling of butter from the churn involves some care in first wiping water or brine from frame of door to prevent dripping on to sample. Then after cutting a fresh surface with a butter ladle a sample of several ounces is collected into a screw cap sample jar.

Samples from print butter and tub butter are taken with a special type of trier, half round in construction, and which by turning into the butter and withdrawing produces a round plug sample. This is placed immediately in a screw capped sample jar, care being taken to avoid loss of moisture on surface of plug which may have squeezed out during sampling. In preparing such samples for analysis, they must be warmed up to a pasty consistency and well stirred.

Sampling of cheese represents some difficulty in securing a representative, uniform sample and avoiding loss of moisture or fat during preparation of sample. Usually trier samples are taken and samples grated if dry, or stirred into a paste if from the soft cheeses.

Dried milk or malted milk products are particularly difficult to sample due to great tendency of moisture absorption. They cannot readily be sampled on humid days or in a damp atmosphere. When samples are taken, these should be with a clean dry spoon from beneath the surface of the powder in the package and immediately sealed in good friction top cans often equipped with double top. With the ever present tendency of fat and moisture separation or moisture absorption, as in dried and malted milks, the question of sample uniformity can become quite a factor in this industry also.

Some of these facts of sampling have been known for a long time by the ore interests. I note in a chapter on sampling from a text[3] published in 1913 some very specific recommendations for frequent and regular sampling of ore. Some of these methods prefer frequent taking of the whole of an ore stream rather than a part of the stream all the time. Grab and hand sampling is considered of little value, and has been replaced by mechanical means. As many as twelve probes per car are used for certain ores, and where lumps are present, the sample may be increased in size. When reducing the large samples of ore, sometimes 10 to 100 tons, to the smaller size for laboratory use specific crushing specifications are given, such as walnut size for the one ton lots down through pea size for the 200 lb. to 5 lb. lots, 20 mesh for the 5 lb. to bottle, and finally to 80 mesh for the laboratory sample.

In the preceding pages, I have presented various sampling methods and have attempted to point out some of the difficulties involved in securing accurate representative samples. It requires but slight reflection to realize that the quality of a single sample or a small quantity of samples can vary considerably. Not only is the element of chance always present in taking the samples as demonstrated by the colored

beads and the rice experiments, but other elements are also always operating such as irregular composition, separation, evaporation, sedimentation, gas losses, and sometimes chemical and physical changes.

Thus, we may conclude that in order to have accurate results from the hands of the analyst, the accuracy of sampling might well be investigated. We should ask ourselves the question, "Have we included every precaution to make our sample truly representative of the product or material of which it is a part?"

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APPLICATION OF QUALITY CONTROL IN WOODWORKING

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Nickey Brotners, Inc.

Few industries offer a greater challenge to the principles and abilities of statistical quality control than do the woodworking industries. It is generally accepted that this great industry is backward and most adverse to new ways and ideas. Perhaps this is true, and if it is, the greater the challenge to all new technological ideas.

Wood has been used by man for countless ages. It has always been the most abundant, the most useful, and the most obtainable material known. The need for an intimate knowledge of what wood is has never been thought necessary. The very ubiquitous attributes of the material has caused men to accept it without question. Wood is in itself a complete substance ready to be worked. Unlike any of the other composite materials that we use which require expert technical knowledge, wood requires little knowledge beyond the simple applications of cutting, sawing, and seasoning.

Because technical knowledge was not considered a necessary prerequisite for the successful operation of the woodworking industry, the use of wood as a material for precision work was never considered. Many new materials were developed to do the work not suited for wood. It is now apparent that a change is necessary. Wood technology has become an important factor to the industry, and new ideas and methods are needed and wanted in order that wood can compete in the markets against the new materials developed to replace wood.

Nickey Brothers, Incorporated, of Memphis, Tennessee has been a leader in the woodworking industry for almost 100 years. The company was founded by Mr. A. B. Nickey, father of the present owner, in Indiana in 1866. From the outset the policy of this organization has been to look to the future; what we have today is fine, but what of tomorrow? When most sawmills were using circular saws, Mr. Nickey set up a band saw mill, the second such mill in Indiana. The output of this mill was greater than any mill in the state. When the supply of large timber began to recede, he went in search of timberlands that would offer unlimited supplies for years to come.

With his two sons, Mr Nickey went south from Indiana to Mississippi in 1898 to survey timberlands owned by the Illinois Central Railroad. After the first day in the forest he had an idea that moved his family and mill south. He had seen a great tree that all the local citizens said was as worthless as a weed, and although he had come looking for oak, it was this worthless tree that attracted him. How could a tree so large and straight be worthless? This tree is the famous gum tree of the south, now one of the most commercially important woods used in this country. It was first cut and sawed as a new commercial wood by Mr. Nickey at his Green River Lumber Co. at Memphis in 1908. A few years later, in 1912, the Nickeys entered the veneer business and set up a mill with four veneer saws. Once again, the willingness to look to the future gave this new company a head start. The gum tree that only a few years before had been considered worthless came up with something new. It was noticed that in an occasional tree there was a

peculiar figuration to the wood, and when the logs were quartered and sawed into veneer the figure gave an odd and beautiful effect. It was the son of the founder that gave us the beautiful figured red gum so popular today.

This discussion is not intended to be a history of the Nickey organization, but just a background to show how it was possible to bring a new science into an old and backward industry. The use of statistical quality control at Nickey Brothers offers no new and startling theories. The methods used are fundamentally basic and simple, yet the results that have come from their use is astounding.

Setting up a program to control the quality of a product has always met with considerable opposition. Most of the opposition to such a program is the result of personal feelings. In most plants the first struggle is to convince management, and after that has been accomplished, to stuff it down the throats of the employees. At Nickey Brothers this struggle did not follow the routine pattern. Management gladly accepted the idea. Any program that would improve the quality of the product and cut down on the number and cost of claims due to badly manufactured products was welcome. Nickey Brothers have always sold their products on a premium market that brought the highest prices in the industry. The old idea of looking to the future was again in mind. When the sellers market disappeared and once again the buyer was in control, could they still sell their products at a premium?

The program was set up with the idea that if the product offered on a sellers market was of the highest quality, then when the situation changed many new and satisfied customers would pay premium prices for our product.

The setting up of the program was not difficult, but to make it work was another story. Most of the key men operating the various machines, as well as supervisors and foremen, had been working at their various jobs from fifteen to thirty years, and a few for more than thirty-five years. The program was started in the veneer plant, and here we met the oldest and most obstinate men in the company. I was told that these men were all like Metropolitan Opera Prima Donnas, tempermental and egotistical, and all I had to do was to figure some way to tell a fellow he was wrong and make him like it. I spent a month asking questions and making friends before I started to hire the quality control inspectors.

The qualifications for the job were rigid. The man had to have a high school education or better, show a high degree of intelligence, and have an attractive appearance and a winning personality. He had to have the makings of a diplomat, a foreman, and an expert operator over whatever machine or operation he was inspecting. These qualifications were hard to fill and harder still when I decided that no one with any knowledge of the woodworking industry would be eligible. It was hard enough to fight natural prejudice from the men in the plant without having first to break down prejudices among the inspectors.

From the start of the quality control program the weaknesses and failures of similar programs in other industrial plants were studied,

and steps were taken to prevent similar weaknesses and failures. The idea of each inspector preparing himself for a bigger and better job has always been kept before these men. By observations and actual participation in the various operations they have been urged to learn the complete operation producing the product they are inspecting. Recently new equipment was installed for rotary cutting veneer. Several new operators were needed who could operate automatic high speed clippers and grade veneer at the same time. The only man available who could qualify for the job was one of the quality control inspectors. This situation has come up several times, and always when a special man is needed or a foreman or supervisor is needed, quality control has a man trained for the job. The thought and plan behind the selection of personnel and the manner in which they operate have done much to break down prejudice and give the statistical element of the program a chance to work.

The success in training men as inspectors as well as for other important jobs can be attributed to the principles of the control program. The constant sampling and analyzing of results obtained from the samples have given these men a better opportunity to study and learn the various operations than the man actually performing the operation. The use of the quality control program to train personnel for jobs outside of quality control has thus proved practical and successful. However, such a program can be very dangerous if allowed to interfere with or detract from the efficiency of the control program in its relation to the quality of the product being manufactured.

Since the program for statistical quality control at Nickey Brothers was started in the veneer plant, it is appropriate that the workings and development of the program in this operation be explained.

In this plant veneers for all uses in all sizes and thicknesses are cut from many species of domestic and foreign woods. In the manufacture of veneers, there are three main quality characteristics: grade, moisture content, and thickness. The first characteristic, grade, is generally determined by visual inspection. The presence of knots, worm holes, stain or scars and rough surfaces caused in manufacture are characteristics checked by this visual inspection for grade. The moisture content and thickness of veneers cannot be checked by visual inspection, and it was to control these two quality characteristics that the control system was inaugurated.

The manufacture of veneers in this plant is carried on in two separate departments, each manufacturing different types of products. The two types of veneers are the rotary cut veneers and the sliced veneers. Rotary cut veneers are used for commercial plywoods and as cross banding and core stock of furniture or wall panels. The sliced veneers are the beautiful face veneers that offer such intricate designs in the grain structure. The veneer in both departments is cut from green logs although the preparation of the logs for manufacture is different. In the discussion to follow, the manufacturing process of both departments will be explained. The development of the control program will be described as the manufacturing process is explained. In the beginning we attempted only to control moisture content and thickness, but like stain in a log, once the process was inoculated with statistical control it spread rapidly.

The cutting of rotary veneers is done on rotary lathes where barked logs, cut to certain lengths, are turned. The preparation of logs for rotary cutting is simple. The logs are cooked in vats of fresh water for certain periods at certain temperatures, depending upon the species of log. From the vats the logs go to the peeling deck where the bark is removed and the logs are cut into proper lengths for the lathes. Rotary veneers at this plant are cut in thicknesses ranging from 3/16" to 1/45". As the veneer comes off the lathe, the quality control inspector takes thickness samples. The samples consist of five observations per sample for use with average and range control charts. There is a control chart for each lathe posted on a large centrally located bulletin board painted in a light buff with four inch letters in bright red, "QUALITY CONTROL".

The control tool used is the average and range chart. The control limits used for each thickness of veneer are calculated with formulas for given standards and were developed from preliminary data taken over a period of six months from at least 1,000,000 feet of veneer of each thickness. The standards adopted have been carefully tested to give the greatest efficiency to the cutting operation and, also, to be certain that when the wet veneer is cut to these standards, the shrinkage that takes place in drying the veneer will bring the thickness desired in the finished product. To insure the exactness of the dry thickness, separate standards have been calculated for each species of wood.

To enable the control inspector to make quick decisions as to how the process is going, another set of control lines has been added to the control chart. These lines represent the specification limits. Thus, when the process goes above or below the control lines, the inspector resamples and continues to do so until he is certain that the process is going beyond the specification limits, remaining out of the control limits but within the specification limits, or is going to return within the control limits. This function of the control chart saves time and waste. If the process goes beyond the specification limits, the lathe operator is notified and he stops the lathe and resets. If the process continues within the specification limits but out of the control limits, the lathe operator will reset if he is just beginning to cut a new log, or he will allow the process to continue to the end of a log if he has cut half or more of the log.

The reason for not resetting each time the process goes out of control is that each log has different characteristics. Some logs are mostly sap wood which is soft and more pliable; other logs are mostly heart wood which is hard. The pressure of the log on the knife must be kept constant; therefore, the fewer times the lathe operator has to stop and back off the log, the more uniform the thickness will be. The specification limits take into consideration the amount of shrinkage in the dry veneer. Thus, if the process is within these limits, the dry veneer will normally hold within its specifications. The specification limits are simply three standard deviations plus or minus the average, and are calculated by use of the formula $\bar{\bar{X}} \pm 3(\bar{R}/d_2)$.

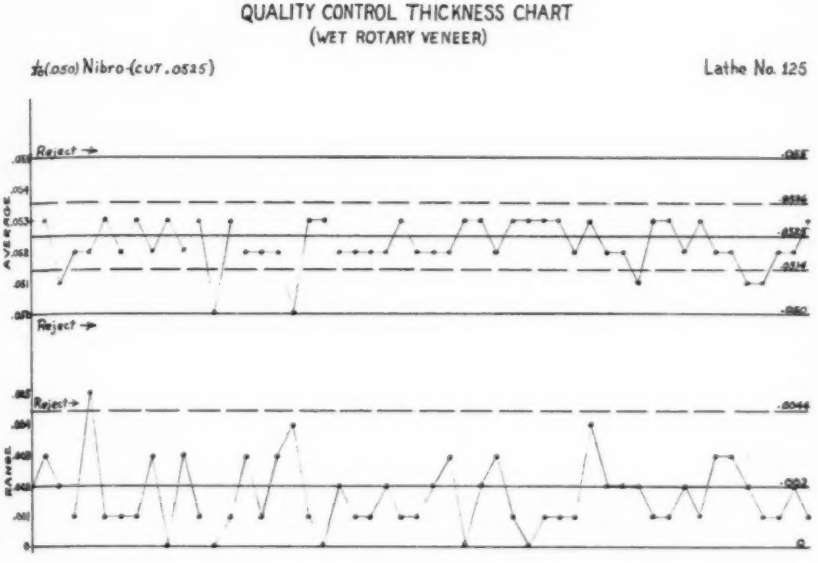


FIGURE-1

Figure (1) shows a typical control chart for checking the thickness characteristic of wet veneer. Samples for this chart are taken so as to represent veneer cut from each log. The veneer, as it passes from the lathe, moves on a conveyor to the clipping table. Here the veneer is cut into sizes that the orders call for. All veneers whose thickness goes beyond the specification limits are rejected. If the thickness is suitable for another thickness it is put in with this group; if it is unsuitable for any order, it is put into crate lining. The control inspector also makes checks on clipper cuttings and records these data on appropriate charts. Here, again, shrinkage is taken into consideration, and standards have been adopted to control this operation.

From the clippers the veneer goes to the green room to await drying. The drying process is carried on by running the sheets of veneer through Coe veneer dryers. The next step in quality control takes place at the dry end of the dryer. When the veneer comes from the dryers it is packaged and is ready for shipment.

The quality control operation at the dryers is basically the same as at the lathes. Here the inspector checks the veneers coming from the dryers for moisture content, thickness, and size. The control chart is used to control the operation. Each customer, when placing his order for veneer of certain size and thickness, also specifies the moisture content. The three quality characteristics thus specified are the subject of the inspector's sampling and analysis. Figure (2) shows the control chart for controlling moisture content with standards applied to control lines and specification limits.

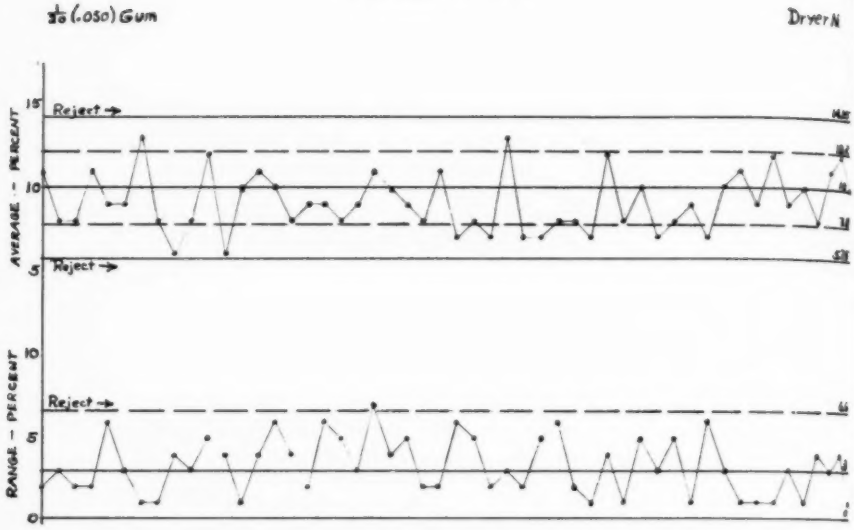


FIGURE-2

The size and thickness of the veneer sheets is sampled in the same manner as on green veneer from the lathes and clippers. The thickness is measured with micrometers calibrated to .0001 inches, and the size of the sheets is measured with steel tapes. The moisture content of the veneer requires greater study and work. The samples are made up of four observations instead of five as used in the thickness and size sampling plan. A selection of four sheets of veneer as observations for each sample is made as the sheets come from the dryer. The veneer comes through the dryer on four levels, and the selection of sheets is made at random, one sheet from each side and the center with the fourth sheet pulled from between the center and either side. It takes months of study and training for the inspector to be able to select representative samples. He must study the various species and know the characteristics of the wood. After selecting the four sheets to be used as samples, they are cut into small sections so that from each sheet several pieces about 3" x 4" are obtained and kept separate in packet form to identify the sheet from which they were cut. Each packet is weighed and the weight recorded. Then they are placed in a fast drying, thermostatically regulated oven and dried completely. After drying they are again weighed and the weight after drying is known as the oven-dry weight.

In our control program we use a scale calibrated to give the moisture content by setting the weights of the scale at the original weight of the packet, and the moisture content is shown on a dial indicator in per cent. However, when this scale is not available, the following formula will give the moisture content in per cent.

$$\text{Moisture content in per cent based on oven-dry weight} = \frac{\text{Original weight minus oven-dry weight}}{\text{Oven-dry weight}}$$

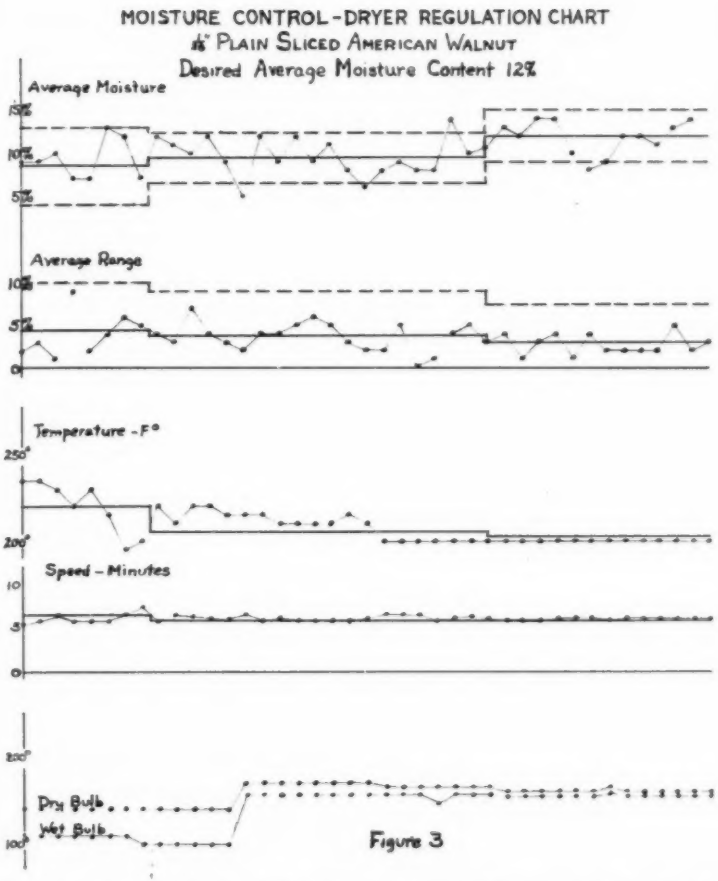


Figure 3

From the results of these moisture tests, the dryer foreman is able to keep the dryers regulated to dry the veneer to the specified moisture content. There are three principle elements in the dryers that must be regulated: the heat, the humidity, and the speed of the rollers on which the veneer is conveyed. Before drawing his samples for each test, the inspector records on a form the readings from each instrument, recording the temperatures at wet and dry ends of the dryers, the wet and dry bulb readings that control the humidity, and the steam pressure that influences the heat and the speed of the rollers. With the results of his sampling in relation to the recorded data from the instruments, the inspector can make an analysis of the drying process and determine the cause when the process goes out of control. The use of a control chart showing the average and range of the moisture content of the veneer and also the temperature, speed, and wet and dry bulb settings of the kiln as each sample is taken, will show the most suitable dryer set up and time cycle for each thickness and species of veneer. Figure (3) shows a section of such a chart. The

elements of temperature, humidity, and speed are changed about until enough data for each setting can be accumulated to determine which settings produce veneers of the best quality.

The quality control inspector has the authority to reject all veneer that does not meet the standards. Reject tags are placed on all crates or bundles of veneer that are too wet or too dry. The wet veneer must be redried and the dry veneer must be set out to condition and pick up moisture. This systematic method of scientifically controlling the quality of the veneers has been very successful. In a period of fifteen months under statistical quality control in this department no claims have been paid, and in all cases claims that have been made were proved to be without backing. The men who, at first, opposed the control program have found it makes their work easier and protects them from the wrath of management when a claim is made for a bad product.

The quality control inspection also checks the number of pieces of veneer to the crate or bundle, or the footage to the crate or bundle if the veneer is packaged in random widths. Along with quality a customer wants to get the correct amount of a product he is paying for, and in like manner there is no profit gained in sending the customer free product. Along with quality the control program offers a guarantee of uniform and correct count.

The quality control program in the sliced veneer department is exactly the same as that in rotary veneer. The drying operation is also the same for both sliced and rotary veneers.

The results of analysis of all the data accumulated has led to many discoveries and methods of getting better quality into the product. On all quality control charts and records appears this motto, "You must manufacture quality, you cannot test it into a product."

Since the advent of statistical quality control in the veneer plant, Nickey Brothers has expanded its use to all other departments. Today quality control regulates the kiln drying of all lumber for the flooring mill and the dimension mill. After being kiln dried, all lumber is again tested by quality control methods for moisture content before being fabricated into flooring or furniture dimension stock. Waste control in both of these mills is controlled by statistical methods as well as the quality of the finished products.

Work has been started to apply quality control methods to the safety program, the importance of which is almost as great as that of the production department. In every phase of the program of statistical quality control, the benefits gained have paid high dividends. The quality of all the many products manufactured can be guaranteed, and all future products such as plywood from the new plywood and panel plant now being built can enter a market with the label of quality. We have brought the wood working industry a means of using wood as a material for precision work. No longer is it necessary for this great industry to be called backward. Today we are as technical and exact as any other industry. The use of statistical quality control has greatly influenced the use of wood as a material to compete on an even footing with any and all other materials.

STARTING A STATISTICAL QUALITY CONTROL PROGRAM AT SWIFT & COMPANY

John K. Wickliffe

The principles of quality control by statistical methods have many and varied applications. The purpose of this two day Quality Control Conference with its speeches and clinics is to review and explain some of the applications in various industries. The purpose of this paper in this clinic is to give you a few of our experiences in introducing quality control by statistical methods at Swift and Company.

We are in the process of learning what this program can do and how to use it. You will hear again and again during this two day session that quality control by statistical methods is a management tool. Industry in general must learn how to use it. We have all been quality conscious for years. We have inspected product by 10% sampling plans and learned that it left much to be desired. We have inspected 100% of the product once, and sometimes twice, only to learn, to our dismay, that we had still passed some defective product.

Statistical quality control based upon the laws of mathematics gives us an insight as to why some of our previous inspection methods often failed. The problem then resolves itself into learning and understanding the mathematical concepts, applying these to industrial processes, and teaching others how to use them. That's all there is to it. The question then may arise: How do you do that?

The procedure used in starting a statistical quality control program is perhaps of mutual interest to both those who have started such a program and to those who will start one. Those who have started such a program have a chance to make comparisons with their own methods, and to use parts of it in their own program if they so desire. Those who have not had the experience of starting such a program can, of course, learn at least one way of doing it, and make such changes as seem necessary for their particular needs.

Just as most individuals are essentially alike in many respects, so it is with companies. Companies, after all, are made up of individuals. Individuals as a rule need to be shown. We cannot be critical of people who resent change - you and I - all of us have the same reaction when some one tries to sell us a new idea. We all agree that it is a good idea, that it has a lot of merit, and it is mighty fine for others - in fact it is just what the other fellow needs, but we don't need it. We are different. While our problems may appear to be the same as another's that is because they haven't been fully understood.

On and on it goes; you have heard it many times, and anyone who has something new to sell must overcome this passive resistence to change. Many of you probably had just such a reaction when you first heard of statistical quality control. How can quality be controlled by statistics? Quality and statistics are two different things. Many of us who had our introduction to statistical methods at the colleges and universities around the country learned how quality and statistics could be related. The problem was the same as has been stated before:

How can these principles be applied?

Those who have had considerable experience in quality control by statistical methods advise that a program be installed slowly, but surely. This is sound advice, because there is no easier way of getting into plenty of trouble than to make a few unsound conclusions about the degree of quality of a particular product. It then follows quite naturally that the resistence to new ideas becomes a benefit rather than a hindrance, because one will, or should be, careful to have all of the answers to help break down this resistence.

In our particular company one of the first persons who had to be sold was myself. I had, in my own mind, been guilty of the very things that have been mentioned before. Sure quality control by statistical methods was fine for some industries, but a meat packing plant is different. My work as a time study man had made me familiar with most operations, and I was very familiar with some operations because I had spent considerable time on method improvement work. I spent quite a bit of time looking at operations and talking to various supervisors about thir processes, trying to find a job to start on. At the time I felt that people wouldn't listen, that they were resisting new ideas, etc. Now in looking back it was perhaps because I wasn't too well sold myself that I hadn't put it over. Sure, I was trying to sell it, but in the back of my mind I wasn't just too sure how to proceed.

In March 1946 I attended the Quality Control Conference at the La Salle Hotel in Chicago and heard of the work being carried on in other companies. After the conference was over I reported back that other companies were getting results, and that in my opinion we should begin selling top management. Selling top management what? What was "quality control by statistical methods?" What would it do? How would we start? Why hadn't something been done?

That was a lot of questions all at once. Some I could answer, others I couldn't. The result was that I was to be given a man and we were to bring in some tangible results and recommendations. We had the ball. It was up to us to produce.

It has been mentioned before that in order to sell something one must be sold himself. Another thing that helps to sell is a sample or a picture. What I needed then was something that would give me a better understanding of the principles involved, and something to show others. The bead box and beads had been effectively used in the schools for demonstrations, and I felt that perhaps if I had one I could use it for demonstrations also. However, it might take considerable time to get one, and I needed something right away.

I happened to be in the dime store on the following Saturday and noticed that the spring marble supply was in. There were small bags of green and blue marbles for a nickel, and in a separate case were some bright red marbles. It might work I reasoned; why not use marbles instead of beads?

I asked the girl how many green and blue marbles there were in a package and she said about 25. I made a rather hasty mental calculation and ordered 20 bags of the green and blue marbles and 48 red

marbles. The girl's mouth dropped open, her eyes grew wide and she asked me to repeat the order. After convincing her that I was quite serious I got my marbles and paid for them.

Upon arriving home my good wife asked me what I had purchased. When I told her that I had bought 600 marbles I got a rather sympathetic look. However, I quickly explained my madness and went to the basement to build a box and a paddle. I didn't have the proper size drill so my paddle was built to hold 5 rows of 10 marbles each. Seems to work just as well. In due time my box was built, and the shellac dry. I then proceeded to run a couple of experiments for my own amusement and to show off to the wife and kids. You have no idea how noisy 600 marbles can be in a plywood box. The wife and kids disappeared and shut the door to keep out the noise, but I had become interested with my new toy.

In order to see what would happen, the following tests were made: 480 blue and green marbles were put into the box with 24 red ones. After a thorough mixing, samples of 50 were drawn and the number of red marbles in each paddle observed and recorded.

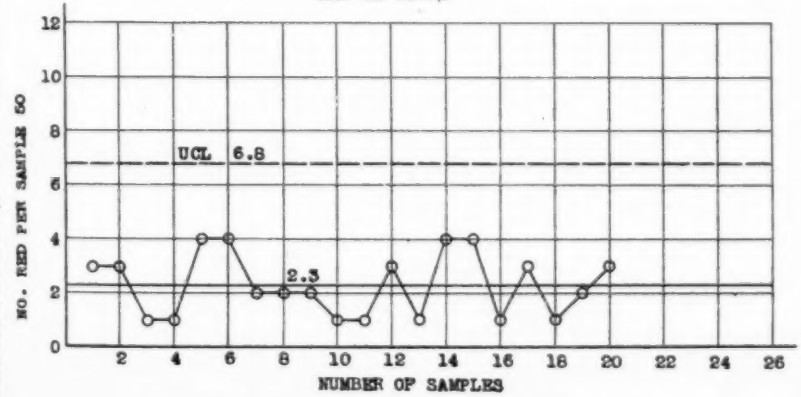
When I had drawn 4 samples I made a sub-total. Additional samples were drawn until a total of 20 had been taken. These samples (number of red marbles in a sample of 50) were plotted on a pn chart. The average was computed and found to be 2.3 red marbles per sample of 50 as compared to an actual 2.375 per sample. The upper control limit was then calculated by the formula $pn \pm 3\sqrt{pn(1 - p)}$, and was found to be 6.8 (See Chart 1).

CHART 1

QUALITY CONTROL

pn Chart — Sample Size - 50

NO. RED MARBLES IN SAMPLE OF 50 OUT OF BOX OF 504 MARBLES KNOWN TO HAVE 24 RED OR 4.75%



DATA SOURCE: First 20 Points Table 1

This simple experiment was important to me, because the whole field of quality control by statistical methods began to make more sense. The lectures that I had heard, the books that I had read began to take on a new meaning. In order to make sure and to convince myself even more I took 60 more samples. I didn't plot these, but no sample went over the upper control limit, nor did it come even close. I had a controlled process. The term of "controlled process" took on a new meaning.

The next logical step in my self-education then consisted of drawing samples from the box of marbles at 7% and 10% in the same manner. Charts 2 and 3 show the results of these and tables 1, 2 & 3 show the results of the eighty samples drawn in each case. The sub-totals of 4 each that had been made in each test showed that there was a definite change as the percentage of red marbles in the box changed. (See Tables 1, 2 & 3).

TABLE 1

SAMPLES OF 50 OUT OF BOX OF MARBLES KNOWN TO BE 4.75% - 480+24 RED

(1)	3	(6)	4	(11)	2	(16)	4
	3		4		2		4
	1		3		5		1
	1		2		2		1
	8		13		11		10
(2)	4	(7)	2	(12)	2	(17)	3
	4		2		3		1
	2		2		3		5
	2		4		1		2
	12		10		9		11
(3)	2	(8)	3	(13)	2	(18)	1
	1		2		1		4
	1		2		3		0
	3		2		2		5
	7		9		8		10
(4)	1	(9)	4	(14)	1	(19)	2
	4		3		1		3
	4		4		3		2
	1		2		0		4
	10		13		5		11
(5)	3	(10)	2	(15)	2	(20)	2
	1		2		5		0
	2		5		1		0
	3		3		3		3
	9		12		11		5

TABLE 2

SAMPLES OF 50 OUT OF BOX OF MARBLES KNOWN TO BE 7% - 480+36 RED

(1) 2	(6) 1	(11) 3	(16) 2
3	4	2	5
2	5	8	3
6	1	4	3
13	11	17	13
(2) 3	(7) 4	(12) 3	(17) 5
4	6	5	2
2	2	6	0
3	4	4	2
12	16	18	9
(3) 1	(8) 4	(13) 2	(18) 2
4	5	6	5
5	4	4	2
3	1	2	2
13	14	14	11
(4) 4	(9) 4	(14) 1	(19) 1
3	2	4	4
6	4	2	1
4	4	3	4
17	14	10	10
(5) 4	(10) 4	(15) 3	(20) 3
3	1	3	4
3	7	6	2
3	3	4	2
13	15	16	11

TABLE 3

SAMPLES OF 50 OUT OF BOX OF MARBLES KNOWN TO BE 10% - 432+48 RED

(1) 3	(3) 5	(5) 5	(7) 3
8	7	6	3
4	3	2	4
5	6	5	5
20	21	18	15
(2) 5	(4) 8	(6) 4	(8) 4
6	5	4	5
5	8	5	7
2	4	7	4
18	25	20	20

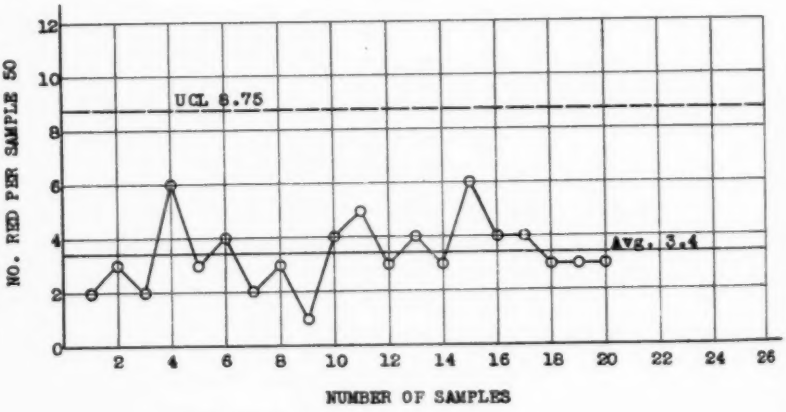
(9)	2	(12)	2	(15)	6	(18)	4
	4		5		7		3
	5		8		3		5
	5		5		2		4
	16		20		18		16
(10)	4	(13)	7	(16)	6	(19)	6
	5		2		3		2
	4		5		3		4
	6		7		7		4
	19		21		19		16
(11)	3	(14)	5	(17)	8	(20)	5
	5		4		5		6
	5		5		4		5
	7		4		10		7
	20		18		27		23

CHART 2

QUALITY CONTROL

pn Chart Sample Size - 50

NO. RED MARBLES IN SAMPLE OF 50 OUT OF BOX OF 516 MARBLES KNOWN TO HAVE 36 RED OR 7.0%



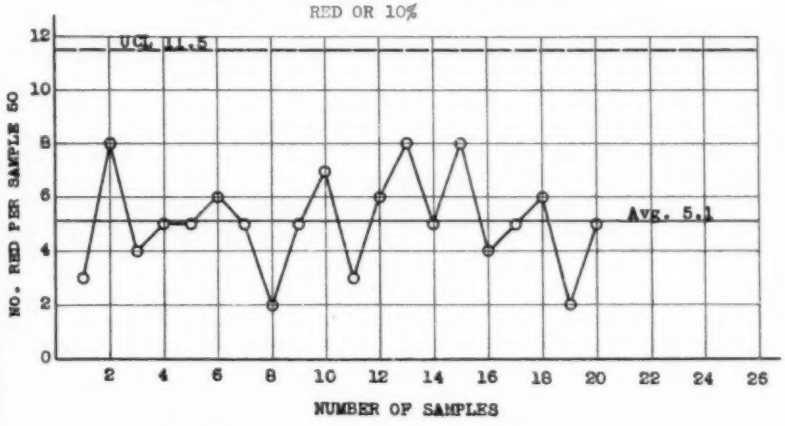
DATA SOURCE: First 20 Points Table 2

CHART 3

QUALITY CONTROL

pn Chart Sample Size - 50

NO. RED MARBLES IN SAMPLE OF 50 OUT OF BOX OF 480 MARBLES KNOWN TO HAVE 48 RED OR 10%



DATA SOURCE:

First 20 Points From Table 3

This was random sampling. This was the principle of the Shewhart chart being unfolded for me and giving me something that I could hang onto.

The results of this experiment were written up, tables of samples made, and the charts carefully drawn. Armed with this I told a Division Superintendent that I had something to show him that was interesting. He was interested and the meeting arranged. The experiment was explained in detail and the charts were shown to him. The fact that all points at 4.75% red marbles stayed within control limits, but that 7% was out and 10% still further out, was a selling point. His next question in effect was: How can we make use of it? We then asked permission to make what might be called a "quality level" survey of our Swift Cleanser line to determine the average number of various kinds of known or classified defects present in each case or container. We said that we would do the work.

This test was run by taking one case of 48 cans from the case-packing machine approximately once per hour. There are roughly 300 cases per hour from this unit. We took a total of 80 cases so that $\bar{X}$ charts (20 samples of 4) could be made or pn charts could be made. Each can was carefully inspected and any defects recorded. Each can was weighed to tenths of an ounce. After the tests had been run and the charts made, a meeting was called of the Division Man and his assistant. The tests and charts were explained. It so happened that the total defects per case were within statistical control, but that none of the individual defects were in control.

An effort was made to explain again the significance of control and lack of control, but it is often difficult to try to explain some of these things. However, it wasn't too important at this meeting. One troublesome defect of 2.7% stood out. We all knew it was there - poor top-crimping. Many of you have tempermental machines - you can appreciate what they are. Some days they're fine, other days they're bad; the same trouble never appears to happen more than once. The Division Man looked at that figure and said "There's the defect we want to eliminate. When the machine isn't working properly let's shut it down. Each machine top-crimps 130 cans per minute - how many cans do we have to examine per hour in order to make sure that one of our two top-crimping machines isn't producing bad cans?"

That was a $64.00 question. We didn't know, but we said we'd find out. Many of you who have had a similar job know how we felt. 130 cans a minute isn't particularly high speed production in one sense of the word, but they come out mighty fast. We said to ourselves "How many cans do we have to look at to make sure we can predict the quality level of this line?"

Like any other problem we went back to fundamentals. We remembered and reviewed our marble experiment. We put the marbles in the box and set them at various percentages. Whether we drew samples of 10, 25, or 50 the average of all samples checked with the percentage we had in the box (or reasonably close). Shewhart and Simon said it would - it was a controlled process. If we increased the percentage of red marbles it didn't take too many samples to go out of control. If it worked on marbles it would work on cleanser.

We took a position on the line just after the cans came from the top-crimping machine. At this point we were actually measuring the process level of the top-crimping machine. We picked up one can at a time, inspected the top-crimp visually, and then tried to pry it off with our fingers. Tony the foreman dubbed us "the Marble Boys With the Iron Thumbs" when we succeeded in prying off a cover that looked good. As time went on over the first two or three days we collected enough points for a pn chart, and constructed one. A chart was kept on each line for a couple of weeks, but in order to see how it worked it was not posted. Each line went out of control on one or two occasions, which was brought to the attention of the foreman, and when the mechanic adjusted the machine the charts came back into control.

During this two week period the process average of defective top-crimps was considerably less (about 40%) on each line in comparison to the previous two weeks check. It must be noted that the first test was made on product ready for shipment; several people along the line had had an opportunity to throw out any rejects readily apparent. The control charts, however, were made on the product just as they came from the crimping machines.

The charts were shown to the Division Man and explained. He was immediately interested, and asked that they be shown to all supervision concerned, and explained. It was suggested that such a meeting would be an ideal time to present the marble demonstration and use it as a background for the charts we were to explain. The suggestion was adopted and the meeting arranged.

This marble demonstration was the first of a series of the same demonstration later given. The demonstration consisted of a brief history and development of quality control by statistical methods. The common practice of sampling 10% of a lot was reviewed and then demonstrated by taking a 10% sample from the box of 504 marbles known to have 4.75% red marbles. As you would expect, this first sample had from 0 to 6 reds on the first try. Two or three tries would be made and the percentage called out and compared to the 4.75% known to be in the box. The points in the meantime would be plotted on a large chart hanging on the wall. A total of 10 samples would be drawn. (See first 10 points on Chart 4). The points were then connected with a red line, and it was explained that this was the pattern of a group

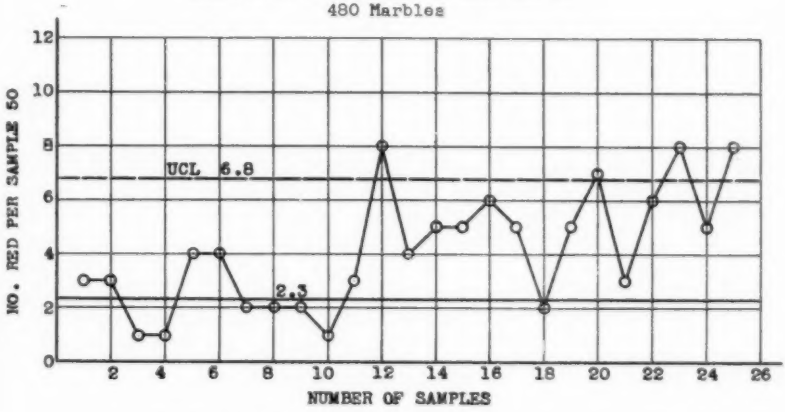
CHART 4

QUALITY CONTROL

pn Chart — Sample Size - 50

NO. RED MARBLES IN SAMPLE OF 50 OUT OF BOX OF 504 MARBLES KNOWN TO HAVE 24 RED OR 4.75%

After First 10 Points Percentage Was Changed To 10% Red or 48 Reds Out Of 480 Marbles



DATA SOURCE:
First 10 Points From Table 1
First 15 Points From Table 3

of 10 samples of 10% sampling. A quick addition would give the average percentage. It was explained that generally speaking a total of 20 points was preferable to calculate a percentage. The average line and the upper control limits were then explained. At most of the demonstrations the formula for 3 sigma limits of the pn chart was worked out. It was then explained that samples of 50 could be drawn from the box indefinitely and that no more than about 3 times out of a 1000 would there be more than 7 red marbles in any one sample of 50.

The group was now told that the percentage of red marbles would be changed to 10%. We then made a corresponding adjustment of the marbles. Samples of 50 were drawn, and the number of red marbles per sample plotted; as can be expected the number of red marbles per sample of 50 would be more than 7 at least twice in 10 samples, and the pattern of points on the chart would show a definite trend upward. (See last 15 points on Chart 4).

With these two examples it became easier to explain what was meant by statistical control and lack of control. Using the marble experiment as a standard example, various plant operations could be compared to the marbles, and it seemed to work very well.

It was mentioned before that even though I had seen the demonstration of beads at Iowa, that I learned more when I had actually performed the experiment myself. Generally after each demonstration one or two people would casually come up to the box of marbles and pull a few samples themselves to see how it worked.

You will remember that our first demonstration was for the benefit of the Cleanser Department Supervision, and it had the desired effect. The mention of "marbles" to anyone who has seen the demonstration gives us a common ground-something to talk about.

After this demonstration was over we began to extend control charts over the whole Cleanser Line. This line is rather interesting in that our tops and bottoms are punched from metal plate. We receive paper for bodies in large rolls which are slit into smaller rolls. The smaller rolls are then put on machinery which forms a continuous tube. These tubes are cut into lengths, the lengths are cut into can lengths and are fed on a conveyor to the bottom-crimping machine. The bottoms come from the punch presses in trays and are placed into the magazine feed of the bottom-crimper. The cans then travel by conveyor to the filling machines where they are filled automatically, and then to the top-crimper. After being top-crimped the cans feed into a high speed labeling machine and then into a case packer.

You can readily appreciate why we liked this line as a pilot application for quality control. We did not interfere with production in any way. We took our own samples, made our charts, and saw the principles of quality control unfold before our eyes. We had excellent cooperation from the supervision of the department and the operator's of the line. It has been mentioned that we had two top-crimp machines, so we posted a chart for each on a post nearby. The two operators would come down together, look at the chart, and then good naturedly kid each other about the points.

Those of you who have control charts can visualize how these first two charts grew to other charts placed along this line at the places where trouble could start. After the charts were established, we of course needed inspectors to carry them on. We have one man on each shift who travels back and forth along this line making inspections and plotting charts. Whenever a point goes out of control the particular foreman involved is notified. If possible the inspector tells the foreman what he believes to be wrong. However, in most cases the foreman or mechanic is so familiar with the process that upon seeing

the particular defect and the fact that it is out of control, he knows how to fix it.

Before supervision had the control charts, a defect had to grow so obvious that it had to be fixed. There were, and are, several people in this line who might be classified as inspectors in so far as it is their job to inspect. They "screen out" any defects found. The important point is that with this "screen out" type of inspection they become accustomed to scrap, and assume that it is normal.

In all fairness to these inspectors they were not responsible. They have other duties in addition to inspection. So that while theoretically we no longer need them so much as inspectors, they still maintain their place in the line, and they do screen out a big percentage of the bad cans that are produced. For example, we have an inspector between the top-crimping machine and label machine. The filling machine and crimping machine run continuously, but the label machine runs out of labels and must be refilled. It only takes a half a minute to refill it, but there are 65 cans filled and crimped in the meantime.

By taking the cans from the conveyor when the label machine stops and placing them on when it starts there is no loss of production. The inspector was there anyway so she could do it. In order to make sure that there are no under-weight cans they must be check-scaled occasionally. The job takes only a few seconds, so the inspector can do it. You can readily appreciate that when this inspector did all that she was supposed to do she was quite busy. You can readily appreciate that since we no longer need her as much as an inspector, she is still there. Yes, there are other possibilities here of improvement, and they are under consideration.

I would like to mention again that this line was an ideal laboratory for us in this first experiment. There were several different types of operations and they were all fast. Anything could happen, and generally did. A new man was being trained as an inspector and in one day the top-crimper, the bottom-crimper, the #1 punch press went out of control, and #5 punch press went out of control twice. The trouble was quickly fixed, and it was an ideal example for a new man. We have had some interesting and valuable experiences in tracing down trouble on this line.

The net results of this initial application are very satisfactory in every respect. Defects per case were definitely reduced. Due to less defects and line blockage caused by defects the production has had a very satisfactory increase per day. Supervision from the line itself on up through the organization are well pleased with the results.

This is the story of our initial application. The same principles that made this application possible are being used in other departments of our business. We have other applications going, we have surveys on others, and we are gradually learning how to do the job. We are right back then to where we started: Learning and understanding the mathematical concepts, applying these to industrial processes, and teaching others how to use them. That's all there is to it.

REESTABLISHING OPERATOR RESPONSIBILITY FOR QUALITY

Wyatt H. Lewis
General Electric Company

When prehistoric man first fashioned a crude club it is reasonably safe to assume that he inspected his own product. He carefully inspected such quality characteristics as weight, grip, and reach, for his life depended upon it.

The early American craftsman also inspected his own handiwork before he peddled it to the villagers. He was craftsman, inspector, and salesman. Customer reaction to the product immediately influenced his methods of manufacture and inspection.

In the modern industrial establishment a vast and complex organization has been evolved as necessary to the production of literally millions of parts of precision design. Specialization has been the watchword of this organization. Management has reasoned that by creating specialists in a cooperative effort more and better products will result. If the craftsman does not have to bother with sales he can become a more proficient craftsman. If someone can concentrate on sales more sales will be made for a given effort.

It is the extension of this reasoning that has created the inspector in our modern industrial establishment. The inspection job has been considered a job separate from that of manufacturing the article. First you make an article and then you examine it. If this is true it seems reasonable to have someone concentrate his efforts on manufacturing while someone else concentrates his efforts on inspection.

What are some of the supposed advantages of separating the inspection function from the "making" function?

1. The operator does not have to interrupt his manufacturing operation to examine the product.
2. The operator has to be taught only how to manufacture; therefore training of operators is simplified.
3. Also the inspector can be trained on inspection techniques and can specialize in the use of inspection devices to appraise more accurately the product quality.
4. The inspector can give an unbiased appraisal of the product and hence, the skill of the operator.
5. Higher production rates can be attained.
6. Lower manufacturing cost can be attained.
7. High quality will result from the critical, unbiased appraisal of the inspector.

Certainly all of the above advantages would seem reasonable to expect. Unfortunately there are some off-setting factors or disadvantages which arise when we place the inspection function in some person other than the manufacturing operator.

1. If the operator does not examine the parts he makes, he tends to lose sight of their quality. He soon becomes a machine turning out so many pieces per unit time.

2. Training of operators becomes over-simplified, and often there is neglect in teaching the operator what quality characteristics are required and how to check the product to see if requirements are being met.

3. When the operator ceases to be his own best critic he loses "pride of workmanship".

4. Soon the operator feels that he has fully dispatched his duty toward the quality of the product if the inspector accepts the parts. There his responsibility ends. It is the inspector's responsibility from then on.

During the war period there existed a set of conditions that dictated a policy of separating the inspection function from the manufacturing function. To mention a few: many new workers had to be trained, pieces had to be had fast, hard and fast lines had to be drawn on quality, cost was secondary to quantity and quality.

When hostilities ceased there was not a sudden departure from wartime practices. A certain philosophy of management had been established and such philosophies, when firmly entrenched, tend to change slowly. Conditions are now changing more as we emerge from the reconversion period and enter a competitive period in our economy. Costs must be watched more carefully and this includes inspection costs. Quality must meet competition at a price, and must be built into the product. Government specifications do not legislate dimensions and other quality characteristics on commercial products. These products must have a high finish, function smoothly, give years of uninterrupted service. To accomplish this the operators must be quality minded. They must feel a responsibility for quality. No longer can industry support a vast inspection force toward which the manufacturing personnel can shift responsibility for quality.

At the Ontario (California) Works of the General Electric Company we have recently endeavored to shift responsibility for quality back to the operator. It was decided that such a policy was not only desirable but necessary. It is the purpose of this paper to describe how this policy is being established and maintained with the aid of acceptance sampling techniques. Results of such a policy justify its extension.

The Ontario Works manufactures all of the electric flatirons for the General Electric Company. During the war it did a commendable job manufacturing aircraft instruments and small sub-assemblies. Due to the rigid specifications and requirements on air force material it was found necessary to double the inspection force over that which was required for prewar manufacture of flatirons. This was not an uncommon experience for concerns manufacturing war material. The availability of an enlarged inspection force proved convenient when troubles developed due to various causes. If too widely dispersed metallurgical properties for a material caused some items to fall outside of hardness specification, it was convenient to have the lot

sorted by an inspector in order to meet production schedules. If a new riveter drove a few bad rivets, these were marked by an inspector and returned for correction. There are many more examples. Operators leaned heavily on inspectors to detect and sort sub-standard quality. It was the expedient thing but it formed some bad habits. When trouble developed the first thing anyone would think of was to throw inspection into the breech.

Since we were authorized by WPB to resume flatiron manufacture to a limited extent, even before VE day, our return to flatiron manufacture occurred under wartime conditions. As our operations gradually shifted from war products to flatirons we unconsciously hung on to our wartime habits. As you all know conditions since VJ day can hardly be described as normal. Standard materials cannot always be obtained, our peacetime product was new to many of our employees who had come with the company during the war. It was natural to hang on to the inspection force to throw it into the breech to sort or otherwise handle an emergency so production schedules could be met. We suddenly realized that our inspection force was not double but triple that which was used per unit prewar. Such an inspection force is not only an expensive luxury, which cannot be indefinitely borne under competitive conditions, but it is an evil. The operators tend to continue their wartime habits of letting the inspector find and sort. The operators tend to shift the responsibility for quality to the inspector.

At this point it should be said that all of the habits developed during the war were not bad. I think we became more quality conscious during the war even though we had an excellent prewar reputation on quality. We now have more controls on quality than we had prewar, and management appreciates the value of these controls. They are anxious to retain an adequate quality control program.

Again considering our problem of too many inspectors, the question was "How can we reduce our inspection force and still maintain our increased controls over quality during competitive peacetime manufacture?" The key to the answer was found in one of the quality control techniques learned during the war.

As you probably know, small electrical appliances are highly finished articles. They are highly polished, nickel plated, buffed, chromium plated and again buffed. The more these articles look like mirrors the more they outshine the competive products on the counter. A large percentage of our inspection force is engaged in inspecting the product for finish defects. Since quality characteristics on finish cannot be measured, they fall into the attributes classification rather than the variables classification. A flaw, such as a scratch on a chromium plated soleplate, is either too deep and long to be acceptable or it is not. It is "go" or "not go".

Furthermore, it should be pointed out that the operator who is doing the finishing operation, buffing for example, has to look at the article he is working on to tell if he has satisfactorily completed his task. You will recognize that this situation differs considerably from an automatic screw machine operation where it is not possible for the quality to be evaluated until the part is completed and falls into

a basket. It differs in other ways. Finish quality is not entirely dependent on the operation being performed at the time. Flaws in the material may affect the end result. If the operator detects a flaw of such proportions that the article will be rejected, he should set it aside and perform no more work on it.

Since the operator, by the nature of the operation, inspects the work, it was suggested that the operator segregate the good parts from the bad and submit completed (good) lots to an inspector who would operate on a lot by lot acceptance basis. Lots failing to meet acceptance tests were to be returned to the operator for sorting or correction. Such a scheme seemed to offer a specific cure for many of our difficulties:

1. The responsibility for quality would rest with the operator.
2. The inspector would again become an inspector and no longer be a sorter.
3. Due to the nature of the operation the operator would have to be fully acquainted with quality standards and work to them.
4. Neither would the operator have to interrupt his operation to inspect any more than normally required by the nature of the work.
5. Pride of workmanship would be reestablished.
6. Since the parts are only sample inspected the operators would feel a responsibility for the quality they pass.

What about some objectionable features:

1. Sampling inspection would allow some defective parts to pass and they would be assembled and rejected on final inspection.
2. The operator might not make an unbiased appraisal of quality.
3. What about costs?
4. What about production rates?

Special skill in use of inspection equipment was not a consideration since all that is needed is a good pair of eyes aided by good illumination. Incidentally, the importance of good illumination cannot be overemphasized—especially where inspection for finish defects is being performed. Operators must have as good illumination provided them as is provided the inspectors. How else can the operators tell what they are producing? We are aiming for a minimum intensity of fifty foot candles fluorescent lighting throughout our factory. Of course good judgment in the use of finish standards enters into consideration, but it was assumed that the operators would possess average judgment on a par with that possessed by the inspectors.

First let us look at the details of the scheme that was established. Figure I shows an operational flow sheet of one of our buffing operations and where the acceptance sampling inspection fits into the flow. Such a flow sheet has been found very helpful in outlining the scheme to operators, inspectors and supervisors—especially if the flow of material is somewhat involved.

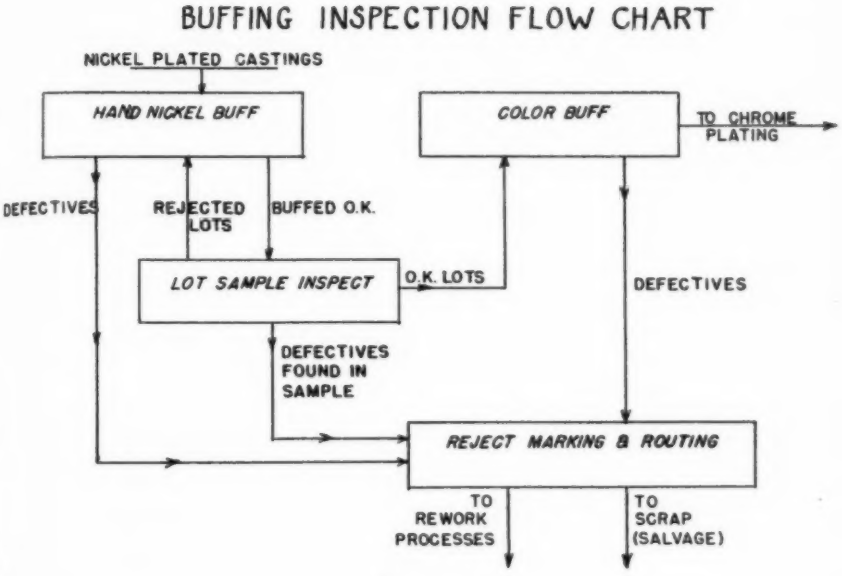


Figure 1

The acceptance sampling plan we use is known as our "normal sampling plan". This plan is almost identical with one of the acceptance sampling plans employed by the Army Service Forces. The plan referred to has recently been published in Professor Eugene L. Grant's book on "Statistical Quality Control".[1] This type has the advantage that a given lot size has a given sample size regardless of the acceptable quality level being used. This is almost necessary where a number of quality characteristics are being inspected simultaneously and the acceptable quality level for these characteristics has varying values.

As an example let us consider a list of quality characteristics with their respective AQL values that are in use on acceptance inspection of one of our flatiron cordsets. These appear in Table I. It will be seen that for varying AQL values the sample size must be fixed for a given lot and the acceptance number allowed to vary for the respective AQL values of the different quality characteristics. Thus, all the inspector has to do is observe the number of defects occurring under each quality characteristic classification in the sample and then to see if the number of defects come within the acceptance numbers specified by the acceptance plan. Of course the plan works equally well in cases where all of the quality characteristics have the same AQL values, as shown in Table II.

While we are looking at Tables I and II it might be well to mention a point that caused some concern when we proposed replacing detailed inspection with sampling inspection. By reference to these tables

1. Table 44 Page 390

TABLE I

CORDSET ACCEPTANCE SPECIFICATION

Characteristic	% AQL
Short circuits	0.25
Open circuits	0.25
Plug missing	0.25
Strain relief not bolted	0.25
Solder bumps on prongs	0.25
Nut missing	0.50
Loose contact	0.50
Nut loose or Screw loose	1.00
Gap between plug halves	2.00
Chipped plug	2.00
Frayed cord or spliced cord	2.00
Long Screw	2.00
Rusty nut or screw	2.00
Over lap plug	2.00
Defective female contact	2.00
Tight plug spring	2.00
Total	19.25

TABLE II

SOLEPLATE ACCEPTANCE SPECIFICATION

Characteristic	% AQL (Castiron)	% AQL (Aluminum)
1. Sandy	2%	----
2. Nicks	2%	2%
3. Peel	2%	----
4. Polish	2%	2%
5. Cut Through	2%	----
6. Nickel Pits	2%	----
7. Metal Pits	2%	2%
8. Bevel	2%	2%
9. Holes	2%	2%
10. Nickel Buff	2%	Buff 2%
11. Scrap	2%	2%
Total	22%	14%

you will notice in the case of the cordsets the total of the acceptable quality levels for all quality characteristics equals 19.25%, and in the case of the chromium plated soleplates the total is 22%. Quite obviously any such percentages as these would not be acceptable quality levels for total defects. We reasoned that it would be a rare occurrence when, on a single lot, all of the various quality characteristics would run just within the limits of acceptability. This has been borne out in actual practice. Table III shows the in-

spection results on several lots of cordsets. It will be seen that the total percentage of defects does in no instance approach the sum of the

TABLE III

				Number of Defects							
MA170125-18	Sample Size	Total Defects	% Def. Sample	Short Circuit	Open Circuit	Gap in Plug	Defective Plug	Frayed Cord	Spliced Cord	Long Screw	Loose Screw
1947 Jan. 27	150	9	6		1		1	1		3	3
28	100	4	4			1	1			1	1
29	100	2	2					1		1	
30	100	2	2						1		1
31	100	2	2				2				
Feb. 1	—	-	-								
2	—	-	-								
K5718305											
Jan. 27	50	2	4			1					1
28	75*	1	1.33	1							
29	50	0	0								
30	35	0	0								
31	75	2	2.67				1	1			
Feb. 1	—	-	-								
2	—	-	-								
*Second Sample	150	0									

percentages shown in Table I. It may be true that a certain element of risk does exist whereby a lot that is high in total defects might be accepted; however, it has been our experience that the inspector becomes quickly aware of a situation where a number of various quality characteristics show defects simultaneously. When he does encounter such a situation he draws it to the attention of a higher authority for further sampling and a decision. Practically, the risk appears to be small and should not scare one away from use of acceptance sampling techniques. If one so wished, an AQL value could be established on total defects which an inspector would not be allowed to exceed. If a still finer line needed to be drawn, a total AQL value could be established for each set of quality characteristics appearing in any AQL classification. As an example we might say that we would be willing to accept a lot of cordsets only if the ¼% AQL characteristic did not exceed a total of ½% AQL. This would complete the acceptance specification but would somewhat complicate it. We have striven for

simplicity to prevent errors and misunderstanding. If we find it necessary, we will add to the acceptance specification.

By now you have a fairly good outline of the acceptance sampling scheme we employed to place responsibility for quality with the operator. You have seen the flow sheet which showed where this type of inspection fits into the process, how defective lots are returned to the operators. You have seen the sampling plan we use and the acceptance specification outlining the various quality characteristics and the percentage AQL for each of these characteristics. All that remains to be covered as far as the plan is concerned is that of inspection reports. Here again we have tried to keep these very simple. Column headings cover the following: Part No., Part Name, Lot Size, Sample Size, Number of Defects Found, Types of Defects, and Disposition (Passed or Rejected). A column is also provided for remarks.

A weekly summary of these inspection reports can be made for supervision and management in one of two basic ways. A conventional p chart can be used for percentage total defects found in the first samples or a p chart giving percentage of lots rejected to total inspected can be used. The latter type is much simpler to compile and it is thought to give a better picture of operator performance than the conventional percent defective chart.

So much for the plan. The next item is to place the plan into operation. There are just two points that need to be emphasized here: first, be sure that everyone concerned understands the plan and how it works; second, check the performance of all concerned when operating under the plan--especially the inspectors. While the plan may look simple to a quality control engineer, remember it is something new to an inspector. Even if your training program was precise in every detail there is a good chance that some ambiguities have crept in. Just to illustrate my point, there is the instance where an inspector thought he was properly following the plan when he was returning defectives found in the sample to the operator when he should have been returning defective lots! Check performance; check some of the accepted lots. Besides the mechanics of sampling there is also the continual check necessary where visual standards and their interpretation by inspectors are concerned.

Before we start discussing some of the results we have obtained there is yet another point that arises in planning and operating an acceptance sampling plan. This point concerns lot size. In most of our installations the lot size has been predetermined by the existing process. For example, in our plastics section, a lot is considered to be one box of handles that passes down the roller conveyor from operator to operator. One box contains 100 flatiron handles. In certain of our buffing operations a lot consists of one load which contains 400 soleplates. In our cord section a lot consists of a day's output of any given type cordset. Lot sizes issuing from our press section run all the way from several hundred up to tens of thousands of parts.

The problem of lot size, as it relates to acceptance sampling, has been discussed fully in quality control literature.[1,2] In general, protection is almost entirely a function of the sampling plan and the

larger the lot size one chooses from, the smaller will be the percentage of inspection done. By reference to the OC curves in Figure 2 it can be seen how sample size influences operating characteristics and amount of inspection performed.

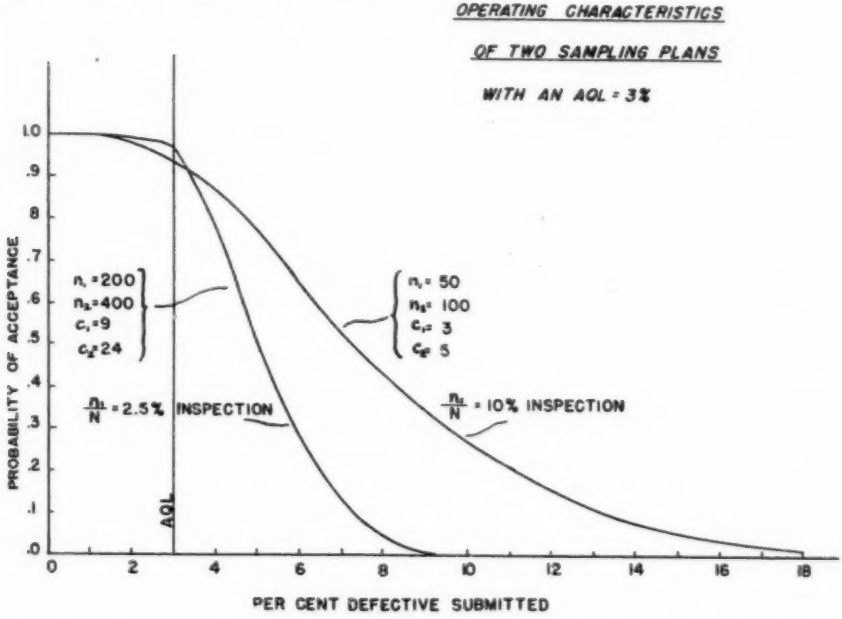


Figure 2

It must be emphasized that in our operation another factor has to be considered. You will recall that we are to return all rejected lots to the operator. Immediately it becomes apparent that large lot sizes have a disadvantage as far as the operator is concerned--especially if he gets many lots returned to him. It means that when he runs into trouble he may be accumulating a large lot and the trouble will not be detected until the large lot has been completed and sample inspected. It also means that if a large lot is returned as defective to the operator, he will have many parts to sort over. Amicable relationships can still be maintained if an occasional lot of a hundred items are returned to an operator for sorting and correction, but these relationships become strained if operators have to sort through a thousand and more parts.

No general rule can be cited; the lot size must be specified for each application. It must be the result of a compromise between such factors as lot tolerance percent defective, amount of inspection by the inspector, practicable size containers to handle through the process, production rates, liability for trouble to occur and whether it appears suddenly or gradually, time required of operator in sorting defective lots, availability of inspectors, seriousness of defects if passed, etc.

So much for the general plan and its installation. Let us now turn our attention to some of the results we have obtained from the operation of such a plan. Such a plan has been in operation for several years in some locations of our factory; however, these early installations were made for the purpose of providing quality control where it did not exist before and at a reasonable cost. The installations made late in 1946 and early 1947 were made for the express purpose of reducing inspection costs and reestablishing operator responsibility for the quality function.

We know that we have accomplished these latter objectives. We do not have to theorize or speculate on the basis of the ratio of inspection to applied direct labor. We know we have physically removed inspectors from certain sections. For example, in the plastics section we used to have five visual inspectors to detail plastics flatiron handles. We have replaced these with two acceptance sampling inspectors and are handling a much increased schedule. In the cord section we formerly had three visual inspectors full time to detail-inspect cordsets. We now have one acceptance sampling inspector who devotes two or four hours per day to this section. Many other examples could be cited. Inspection costs are definitely being slashed.

You might say, "Sure, why wouldn't your inspection costs be decreased. You are now having the operators doing their own inspection. You have merely transferred inspection costs from an indirect labor charge to a direct labor charge." Of course my reply to this would be that what you say is partially true. As a matter of fact you will remember that one of the objectives of our policy was to get the operators to inspect their work.

In order to satisfy you and get a true picture of what this policy has afforded from a cost standpoint we should look at the over-all costs of inspection and operating (applied direct) labor. Since our operators are paid on an incentive pay plan it was necessary to have new rates established on jobs where formerly the operators did not do their own inspecting but now inspect. Comparison of these rates before and after the policy was established afford us an easy means of studying the over-all cost picture. Table IV shows how much inspection costs us, regardless of who does the inspection. Two typical parts

TABLE IV
INSPECTION COSTS COMPARISON
Detailed Inspection vs. Acceptance Sampling
Plastics Flatiron Handles
(Basis 1000 Handles F-13)

	Detailed	Acceptance
Sanding Operators	$0.00	$1.91
Buffing Operators *	0.00	0.00
Visual Inspectors	7.88	0.00
Inspection Leader	4.12	—
Roving Inspectors	—	3.79
Acceptance Inspectors	0.00	3.79
	$12.00	$9.49

* Buffing operator inspects as he buffs.

Cordsets
(Basis 1000 Cordsets)

	Detailed	Acceptance
Operators	$0.00	$0.00
Visual Inspectors	6.57	0.00
Acceptance Inspectors	0.00	1.32
	$6.57	$1.32

are shown and total inspection costs per unit are shown before and after the new policy was established. You will see we have actually made a cost reduction besides accomplishing our objective of getting the operator to look at his work and take pride in its quality.

You might say that this limited cost picture does not tell the whole story. How are production rates affected? How much productivity of the machine and the operator is sacrificed while the operator is inspecting? Table V gives this comparison. You will see that as far as

TABLE V
PRODUCTION RATE COMPARISON
Detailed Inspection vs. Acceptance Sampling
Index = 1.00 Before operators started inspecting function.

Plastics Section

	Detailed	Acceptance
Sanding Operator	1.00	.93
Buffing Operator	1.00	1.00

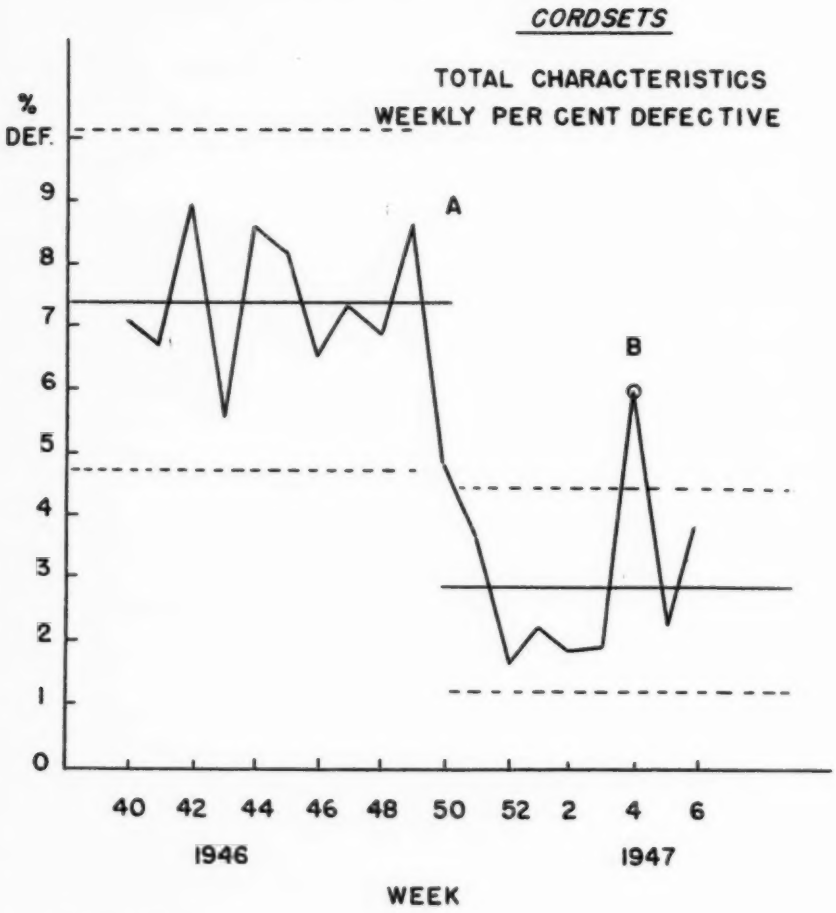
Cord Section

	Detailed	Acceptance
Operators	1.00	1.00

the theoretical rate is concerned we have sacrificed little. Actually we have sacrificed even less, for now the parts we make are good parts and do not have to be scrapped or reworked and hence lost as usable production.

So much for costs and production rates. How about quality? Product quality should be considered at two points when we are making a comparison between quality under the old arrangement and under the new. The first point is the quality level of the product passing from the operators to the inspectors and the second point is the quality of the product passing from the inspectors to assembly, stock, or the ultimate consumer.

Let us consider the quality at the first point. When we had detailed inspection in our plastics section, 25% of the plastics handles were returned for resanding or rebuffing. Now only 5% of the lots are returned for all causes. Since the rejected lots have only a conservative percent defective pieces, the quality coming from the operators has improved at least five fold and more nearly twenty fold!



NOTES:

A = STARTED ACCEPTANCE SAMPLING

B = LOOSE SCREWS. DEFECTIVE LOTS REWORKED.

Figure 3

Figure 3* shows the shift in quality level on cordsets coming from the operators. The average percent defective shifted from a mean of 7% to a mean of 3%. Of course it is true that the girl who wraps the cordsets now inspects while she wraps. This was not done previously, for the detailing inspectors had performed this operation. We are actually obtaining an inspection almost as good as we had before but at a much more economical rate. As far as short circuits are concerned we are protected, for we have installed an indicating device on each of the assembly machines that flashes a warning if a cordset is as-

* See page 246 for footnote.

sembled with a short circuit present. This inspection is practically free. Formerly our visual inspectors tested each cordset by plugging it into a flatiron in series with an indicator light.

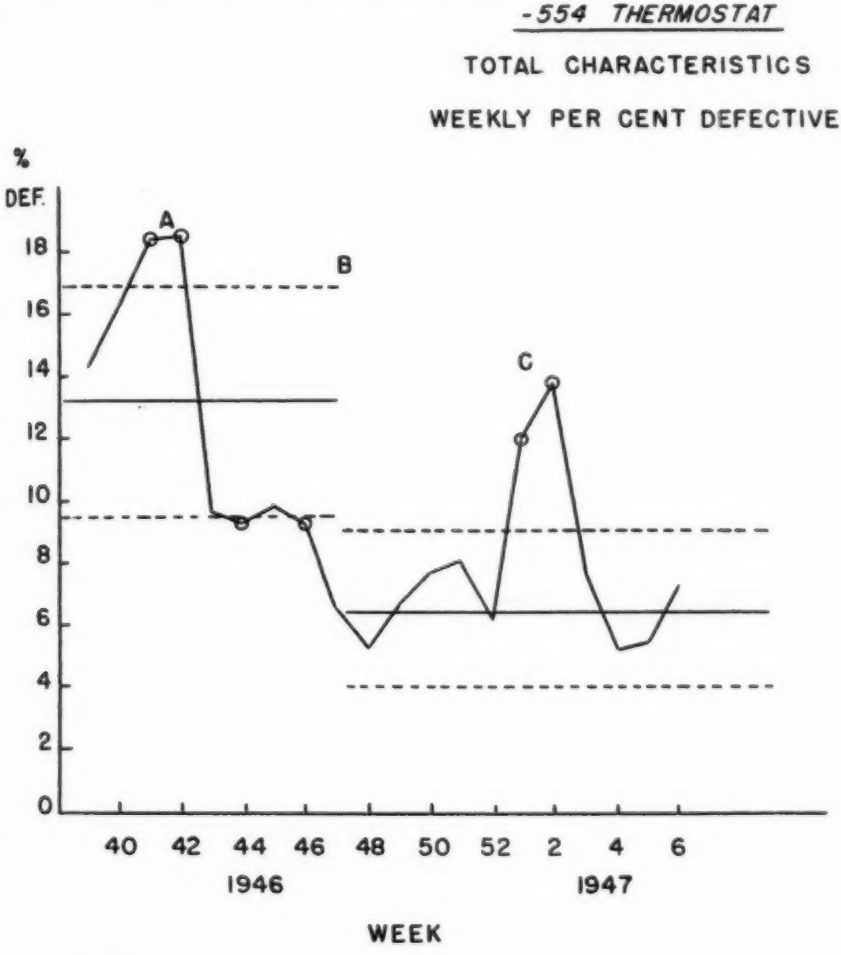


Figure 4

Figure 4* shows the change in quality level in our thermostat section when we changed from detailed inspection to sampling inspection. I

* See page 246 for footnote.

take time to cite this example for it demonstrates a case where much of the detailing inspectors' time was devoted to testing each thermostat for contact pressure on a go, not-go basis. Now the contact pressure characteristic is controlled by means of an $\bar{X}$, R chart using variables measurement. The remaining characteristics, which are necessarily attributes characteristics, are controlled by our normal acceptance sampling plan.

There are other examples, but we must hasten on to take a look at what has happened to the quality of the products passed by the acceptance sampling plan. In those cases where the product goes directly to tne consumer without further tests on subsequent assembly operations we must evaluate quality by means of our quality control inspection performed by the Engineering Laboratory. In the case of cordsets no significant difference in quality can be detected on the basis of daily samples.

We can more thoroughly evaluate the quality of products or parts which pass an acceptance sampling station and are subsequently inspected on final inspection either visually or by performance tests. Such is the case with plastics handles. Here is a critical test, for our previous record resulting from 100% inspection by inspectors in the plastics section, resulted in an entirely negligible amount of defective handles reaching assembly. We are now getting a few defective handles reaching assembly, but they are so few in number that we can well afford to replace them on the completed flatirons rather than to support an expensive plastics inspection organization. In the case of thermostats an actual improved performance on final test has resulted from closer control in the thermostat section.

There is another advantage that has accrued from replacing detail inspection with sampling inspection. We have found that inspectors that are operating on a sampling basis are more inclined to carefully appraise the product than those operating on a detailing basis. Other observers have seen this happen again and again. The generally accepted explanation is that the dull routine of detailing is deadening to the senses. Inspectors tend "to get into a rut" so that if anything new comes along it is not properly noticed simply because it is not a part of the established routine. Another thing that happens; especially on detailed inspection for finish defects, is the tendency of the inspectors to depart from established standards. On recurring finish characteristics the inspectors demand greater and greater perfection. This is popularly termed "tightening up". I suppose after one has looked for and at hairline scratches all day any scratch, no matter how slight, gains importance in the mind of the inspector until it looks to be of tremendous proportions. Thousand of dollars of unnecessary rework losses are created inadvertantly in this manner. An inspector operating on acceptance sampling is more inclined: first, to recognize and critically consider development of new characteristics; second, to more carefully appraise defects

* Control chart limits for these figures were calculated using the "Moving Range Method" for per cent defective. Prior to acceptance sampling, results were based on 100% inspection over a period greater than that appearing on the charts. The formula and method used is described by Hammer, Preston C. "Limits for Control Charts", INDUSTRIAL QUALITY CONTROL Vol. II No. 3 Page 10, November 1945.

found in the sample against established standards. I think there is also a psychological factor. The detail inspector is inclined to work on the basis of "Can I reject this part", whereas the acceptance sampling inspector works on the basis "Can I accept this part". The positive approach is much to be preferred over the negative.

Another thing, if sampling inspection reduces the number of inspectors, more and closer supervision of inspectors is possible More attention can be paid to inspector performance against quality standards. Along this same line the whole training program is greatly simplified. Rate of turn-over in the inspection force does not present a serious problem when there are fewer inspectors to train.

At this point I should like to digress long enough to tell you of an important inspection principle we have discovered which greatly decreases inspection costs. This applies particularly where detailed inspection is necessary such as chromium plated parts coming from our plating conveyor. There are two ways to perform the inspection; first, the parts can be accumulated in boxes and then taken to an inspection area, or secondly, the inspection can be performed as the individual parts come from the machine or process. The latter is much to be preferred. In quality control literature the basis for this preference is that minute by minute information on the process is thereby afforded. While this is a very important consideration, I wish to draw your attention to another. The pieces inspected per hour by an inspector are greatly increased when the inspection rate is geared to a machine or process. When inspectors pick pieces out of a box they not only consume time in handling the pieces in and out of boxes, but they tend to set their own pace which is inclined to lag. Where ever possible, inspection should be performed as the parts come off the machine. If one inspector cannot handle the output of the machine, two or more inspectors can be used. We have found inspection rates can be almost doubled and hence inspection costs greatly diminished by this means.

The cost results of our policy covered thus far in our discussion refer particularly to inspection costs. I have alluded to certain other cost reductions which should be recapitulated for emphasis. There is not only reduced inspection costs, but also reduced rework costs. This cost reduction arises in two ways. First, operators are careful not to produce or pass parts that will require reworking or scrapping, for now they must sort these out instead of the inspectors. Secondly, the inspectors do not create unnecessary rework by departing from the standards in the direction of demanding perfection.

Scrap and rework losses for the total operation rose steadily during a period of several months last year. It is notable that those sections which had had an acceptance sampling inspection installed in them held to consistently low losses. Now that we have extended this type of inspection, the total scrap and rework losses for the factory are showing a good downward trend. While acceptance sampling cannot claim full credit for this, it has contributed a big share to the total reduction in losses.

Now to summarize. On certain types of manufacturing operations specialized inspection is required. In these cases management rightfully turns the inspection operation over to an inspector. Other

types of manufacture, where attributes characteristics such as finish are important, the operator should inspect his own work. He has to do this in order to properly perform the finishing operation, which he can do without leaving his machine or interrupting his task. The operator feels a greater responsibility for the quality of the product if he inspects his own work. Since he is making inspection decisions, he is better acquainted with acceptance standards and has a better chance of producing to these standards. Pride of workmanship is re-established in the operator.

A check against biased quality decisions is established by means of lot by lot acceptance by a well qualified inspector.

During war production certain conditions existed which overemphasized the specialized inspection function. This tended to shift responsibility for quality from operator to inspector. Our recent efforts have been directed toward placing a large portion of the inspection function and responsibility for quality back in the hands of the operators.

Such a policy has been made possible, strangely enough, by a quality control technique learned during the war production period. This is acceptance sampling inspection.

This technique has enabled us to retain quality controls we did not have prewar and at the same time reduce our inspection force. Both are imperative to keep ahead of competition on the basis of quality and costs.

An acceptance sampling plan is established by working out a flow sheet of the process showing points of inspection and flow of parts. A sampling specification is established which places sampling on a sound statistical basis. Several such plans are available in the literature in table form.[1,2] A quality specification is made which lists the acceptable quality level for each of the quality characteristics pertinent to the product under consideration. Report forms are established for recording inspection and acceptance results. Summary reports are made on a weekly basis for the benefit of management.

The matter of lot size is determined by a number of factors. Although large lot sizes may be desirable from a statistical standpoint they are objectionable if the operator has defective lots returned to him for sorting.

When all of this has been established as the plan, be sure everyone concerned understands it and check performance when the plan is in operation.

The acceptance sampling plan has accomplished a reduction in total inspection costs including inspection time invested by the operator. Production rates have, in most cases, remained unchanged. In no case have they been affected more than 10%. Actually a gain is made, for now parts produced are good parts which don't require reworking.

Quality has not suffered. It actually shows improvement. If the parts are produced right the first time, the quality is better than if

they have to be reworked.

Scrap and rework losses show a strong downward trend.

Inspectors, who are working on an acceptance basis, are better able to properly appraise the quality of the product and adhere to finish standards than are detailing inspectors. This results in better quality of the accepted product and diminishes the unnecessary losses occurring from rejection of perfectly acceptable products.

By returning the responsibility for quality to the operator and checking him with acceptance sampling procedures, we have helped attain our goal of "more goods for more people at less cost".

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TEACHING STATISTICS TO ENGINEERING STUDENTS

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During 1946 there appeared, in the JOURNAL OF ENGINEERING EDUCATION, several articles by Holbrook Working and Leslie E. Simon on the subject of statistics instruction in engineering schools. These articles present in formal shape arguments that have been buzzing around in the heads of many people, in and out of academic life, concerning the addition of a good course in statistics to engineering curricula. They give new impetus to the movement to introduce such courses into the engineering curriculum, and in fact a good many schools now offer such instruction, or something approaching it. It seems reasonable that men now in industry should be interested in what is going on behind the collegiate wall, partly so they may know what kind of human resources may be added to the production stream in time shortly to come, and partly (in the case of those now engaged in statistical work in industry) to know what sort of competition these new trainees are likely to offer men with perhaps less formal training but more practical experience.

How much statistics is it likely our schools will attempt to give in a four-year engineering course? Probably not much. The engineering curriculum is already overcrowded, and the standard reply to those who propose new courses is, "What do you propose to eliminate from the present curriculum to make room for the new course?" Such a question is not easy to answer. The plain fact is that four years is too short a time to convert a high school boy into even an apprentice engineer; far too short if we expect the engineer to be, not merely a skilled technician, but a thoughtful and informed citizen. There are sound arguments for having engineers study history and economic geography, to say nothing of philosophical subjects which may be of little practical application but are needed to supply a basis for mature thinking. The movement to "broaden" engineering curricula is not new, and the statistician who enters it must elbow his way among many other specialists who feel, mostly with excellent reason, that the engineer needs to know something about their subject too.

We have here posed a dilemma. If we do not broaden engineering curricula, in particular by the introduction of courses in statistics, the engineer will be inadequately trained. But if we remove courses now given and substitute others, the engineer will still be inadequately trained due to the loss of courses removed. It follows that we cannot stick by our idea of what constitutes adequate engineering education and also stick by the four year curriculum, and this is no doubt the goal toward which we are working -- possibly the requirement of two years of college work as prerequisite for admission to an engineering school.

If, then, by this means or by some other, it becomes possible to enlarge the field of engineering study, statistics should and no doubt will occupy an important place. Two questions suggest themselves: (1) At what time during their college life should students study statistics? and (2) On what level should the statistics be taught?

As for the time, my feeling is that some elementary training in statistics should be given in connection with the first course a student takes that gives him an opportunity to make measurements. This will ordinarily be a laboratory course in physics or chemistry. The course might not be called "statistics", but perhaps merely "precision of measurements." It should not deal at any length with statistical theory, but merely introduce the concepts of error, probability, statistical estimation, and the like, and teach the student to compute simple statistics such as the mean and standard deviation. If the student never had another course in statistics, this elementary training in connection with measurements would make it possible for him, with a little intelligence and initiative, to continue study in the field by himself at some later time.

A survey course in industrial statistics should be offered at the beginning of the junior year. No attempt should be made to teach statistics in any rigorous sense during this introductory course. Its purpose would be to acquaint the students with some of the history of statistics in mass production, and to help him fit statistics into the general industrial picture. Such a course, meeting perhaps twice a week for a quarter or semester, might well be required of every engineering student. The reason for giving this course in the junior rather than the senior year is that one must allow sufficient time, after the survey course has been completed, for students who want to pursue the study of statistics to do so, and no worth while program of study can be completed in part of an academic year.

Following the survey course, an institution might well offer as much statistics as its staff was capable of teaching, provided there was a demand for it. We have adopted this procedure at N. C. State College, and it may be that the best way to conclude these remarks is to describe our plans, which pretty well express my own convictions, since I am mainly responsible for them.

N. C. State College is on a quarter basis, each quarter lasting about twelve weeks. Three quarters constitute the academic year. This fall (1947) we shall offer, during the first quarter, a survey course in industrial and engineering statistics such as I have described, meeting three times a week. This course will be required of all industrial engineering students and optional for others. I plan to divide the course into two halves. The first will deal with history -- how statistics as we know it today came into being, and how it began to be applied to engineering problems. The second half will cover a few simple, useful techniques; we will make some control charts, carry out a few sampling experiments, and talk briefly about the ideas behind these devices without being profound. Beyond this I do not expect to go.

The second and third quarters will be elective for all students, and in them I plan to go through my book, chapter by chapter, enlarging a little here and there but essentially trying to impart a familiarity with the text and the methods there presented. We shall deal with sampling inspection in some detail, including double and sequential sampling and AOQL methods. We shall discuss the use of control charts. We shall talk about statistical estimation in some generality, and study briefly the subject of tests of significance, a matter of great

practical importance to any scientist. We shall look briefly at the nature of industrial and scientific measurements, and conclude with a quick survey of the scientific planning of experiments. This material will more than fill up the year, without permitting any really careful study of the theoretical and philosophical notions behind the methods.

Students who desire this additional background will be offered an opportunity to get it during their senior year. The second year will be devoted to going over the book a second time, but this time in a critical and rather leisurely manner. We shall probably devote the whole of the first quarter to a study of probability, bringing in illustrations from the text and other sources for examples. However, only a minimum of distribution theory will be included; most of the important theorems of mathematical statistics will be presented without proof, or with a mere sketch intended to make the result appear reasonable. By the time the student finishes his senior year in statistics he should know the how with some thoroughness and have at least some notion of the why.

Additional study will be at the graduate level. Students doing graduate work in statistics will probably take some courses under the Mathematical Statistics faculty at Chapel Hill, in addition to applied courses at Raleigh. They will study the subjects of correlation and regression, which have been left out of the text. They will, in all probability, take courses in matrix algebra and theory of functions, to say nothing of advanced calculus. Beyond this we have no plans, since graduate study in statistics as in other fields is necessarily tailored pretty much to fit the taste and interest of the individual student.

We thus hope and expect, during the years to come, to present to industry (a) a considerable number of engineering graduates who have been introduced to statistics and have some idea of what it is all about; (b) a smaller, but I hope not too small number who can use statistical methods in engineering problems with some skill and even comprehension; and finally (c) an occasional individual who combines with a sound statistical training a thorough knowledge of some field of scientific or engineering application. While all these are important, I have special hopes for the last group. Their number will be small, but by bringing into scientific work a combination of statistical and scientific training which has until now been almost unattainable, they should bring new vitality and impetus to scientific progress.

QUALITY CONTROL AND CHEMICAL SPECIFICATION

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Specifications have an important role in quality control in the chemical industry. They are concerned with the selection of raw materials, the inspection of the product in process, and the inspection of the final product. A specification is a written statement defining the standard of quality of a thing required for a certain purpose. It is a very important industrial tool because it can bring about that "meeting of the minds" of different people in different positions on quality. By means of an efficient specification, a testing or inspection department can routinely determine the suitability of any unit for the purpose for which the specification is designed. This is exceedingly important in large industries where men of experience cannot spend their time examining all products and raw materials. A well designed specification is a profitable tool; an inefficient one can be a liability.

In order to create a chemical specification which will define quality, the following fundamentals must be observed:

1. We must select for measurement all the characteristics of the article which are known to be of importance to control for the purpose intended.

2. We must define a method of measuring each characteristic which is precise enough for the purpose and is related to the quality characteristic under consideration.

3. We must choose a standard of quality which truly represents the best balance between the quality requirements of the consumer and the quality capabilities of the production process.

All too frequently chemical specifications have been established arbitrarily or from past precedent instead of by a scientific method. If a specification is going to do its important job, it must be made for that job, and its creation will require as careful design and workmanship as the development of the process itself. In some cases it is necessary to make arbitrary decisions, but the chemist or chemical engineer who is setting a specification should use his knowledge of chemistry and production operations coupled with his understanding of the statistical nature of materials, men, and machines.

The quality control engineer should learn how to set specifications which are complete and which actually fix the quality definition, but which do this in terms that are practical, realistic, and possible of profitable fulfillment. They should provide the required assurance to the user and fairness to the supplier.

In establishing a specification for a chemical raw material, all the characteristics, chemical and physical, should be considered, and those selected which are known by chemical theory, production history, or correlation analysis to have a significant effect upon final product quality, process efficiency, safety, or cost. This list

may be reduced by eliminating those characteristics which do not vary significantly compared to the requirements. Correlation analysis and variance analysis are two scientific methods for choosing those characteristics of importance. Control charts will accurately measure the variation and reliability of any characteristic.

The chemist should also make a study of the accuracy, precision, and reliability of any method given to measure that characteristic. He should make sure that the test method is precise enough for the purpose required.

The standard of quality should be selected to establish the best economic balance between the costs of the raw material, the costs of manufacture, and the value of the finished product. When a final product specification has been fixed by the consumer, the raw material standard and the process methods must be designed to fulfill the consumer's requirements. The process must be designed to produce the required final product quality from the available raw materials. In this case the process design engineer must strike a balance between the quality of the raw material and the method of the process to produce desired final product. The engineer should consider the economic effect and feasibility of using lower raw material quality with improved process methods or conversely, of using simplified process methods and improved raw material quality. In any event the engineer must work within the range of available raw materials.

In-process specifications are determined in the same general way. Their purpose is to fix the quality and variation of the in-process material at some point during manufacture at which it is profitable and desirable to make an inspection of the in-process material. In this case the relative economic advantages of passing or rejecting or reworking widely varying material at this point in the process should be considered. The limits should not allow any material to pass which is beyond the ability of the remainder of the process to bring within specifications. Statistical studies form the basis of the scientific selection of in-process specifications.

The final product specifications for chemical materials are usually determined by the consumer since the chemical material is frequently the raw material for another process or product. In this case the specifications should be created by the consumer in accordance with previous considerations, and the job of the supplier is to design a process to meet these specifications or to determine if his present process will meet the specifications. In other cases final product specifications are set by the producer to meet a general demand for a given quality of a chemical material. Sometimes several grades of this material are specified to give the consumer a variety of choice. In this case the economic balance between the cost of material and its value is made by the producer. In any case, the three fundamentals of a chemical specification must be observed, and the selection of the characteristics, the methods of measuring each characteristic, and the standards of quality should be based upon careful scientific and economic studies in which statistical data is of important assistance.

To compare a productive process with a product specification, the control chart is a most effective tool. After the control charts have been set up on the desired properties the following questions should be asked on each control chart.

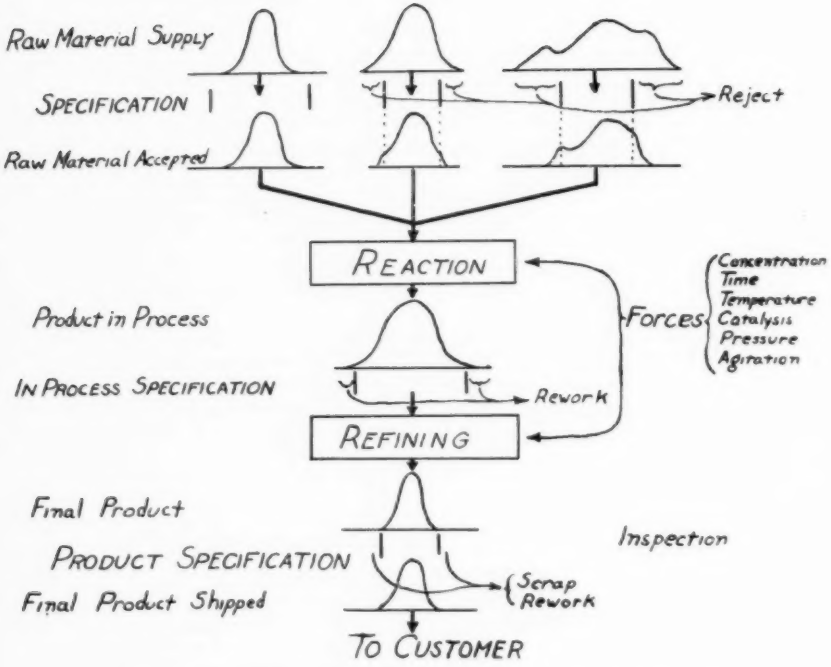
1. Are the data within control? If a process is within control the future quality variations of the process can be predicted within limits with reasonable assurance. However, if lack of control is shown, no prediction of future quality can be made, and the remaining questions will not apply. If the process is not in control, then investigation of a trouble shooting nature should be undertaken to find and eliminate the causes of lack of control. All efforts should be directed to bringing the process into control before proceeding with questions two and three.

2. Is the quality average within specification? If the quality average is too high or too low it may be shifted by changing the process controls. Sometimes it is not known how to do this. In such cases this should be assigned as a problem to development or process improvement groups.

3. Is the range of variation within specification? If the three sigma limits for individual values lie within the specification, then the process may be judged satisfactory. If the variation is too great, then an investigation should be conducted to narrow the limits on raw material specifications, process control, or methods of tests. This may require assistance from development and research groups.

One of the most important factors to be considered in the application of specification to chemical products is the precision of the chemical tests used to measure quality. Unless the accuracy of the test methods are comparable to the requirements of the process and the specification then difficulties and confusion will result. Under these conditions it is sometimes possible to substitute tests or, perhaps, to measure another factor which correlates with the property in question. The control chart and the correlation tests are excellent methods of doing this.

The chemical specification can be one of the most important methods used by the chemical engineer in process control. It must, however, be used with an understanding of the factors in the chemical process and the statistical nature of materials and forces. It is hoped that this discussion will aid in starting a trend toward more useful chemical specifications.



The Role of Specifications in the Chemical Laboratory

This drawing shows the statistical nature of the variables in a simple chemical process, and the controlling influence of specifications. The process illustrated is one in which several raw materials are mixed and reacted, producing an intermediate product which is then refined to the finished product. Three distribution curves at the top represent different variations in some of the characteristics of the raw materials. The raw material specifications are illustrated by the dividing lines below the distribution. Their function is to pass material between the lines and reject material beyond these limits. The success of the specification depends on the precision of the sampling and tests specified. The type of distribution of the material accepted is illustrated below the specification limits. At the end of the reaction the variation in material produced is illustrated in comparison with an in-process specification which will attempt to limit the variation at this point. The final step of refining will reduce the variation in some of the characteristics and should produce a product within the limits of the final product specification. In these ways the specification is an integral part of the design and control of the process, and the successful operation of the process will depend to a great extent on the care and skill used in designing the specifications.

THE FUNDAMENTALS OF CORRELATION

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Correlation is an entire field in itself. Many volumes in a statistics library, as well as college courses, are devoted to it alone. Therefore, this paper can be only a very general discussion of the high points.[1]

What is Correlation? In every day conversation the term "correlation" is used to mean similarity, covariation, or relationship. Thus, when the statement is made that there is a high degree of correlation between prices of corn and prices of hogs, it merely means that when one series varies, the other does likewise. Similarly, in statistics, the term "correlation" refers to the covariance of two or more series. However, the statistical meaning embraces more than this, in that it refers to the actual covariation, the methods or procedure employed to obtain the extent and direction of that covariation, and to the description of that measurement.

For example, we know from experience that tall people generally weigh more than short people. However, we know of many cases where a short person weighs more than a taller one. In order to determine whether or not there is a relationship between height and weight, we can measure mathematically the variation between two series of data representing heights and weights of an adequate sample, and if we find there is a definite relationship existing, it can be said that these two factors are correlated.

TABLE 1

Trial Number	Inches Drop of 1/4 lb. Ball	Force in lbs.
	X	Y
1	7.9	59.3
2	9.2	60.8
3	10.5	68.3
4	10.1	73.5
5	10.7	75.8
6	9.9	79.5
7	10.3	81.8
8	11.4	84.0
9	11.1	86.3
10	10.3	88.5
11	12.0	90.0
12	12.6	97.5
13	12.9	104.3
14	12.4	99.8

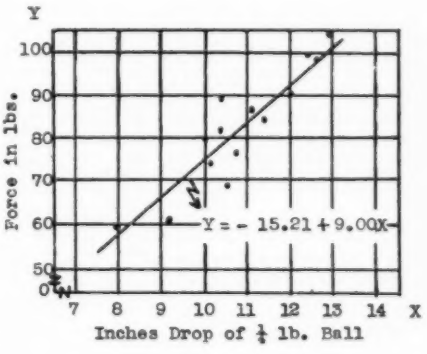

FIGURE 1

[1]The writer is more familiar with applications of statistics in economics and business than in industry. However, correlation analysis and interpretation of results are precisely the same whether we are considering economic factors or production data. In the first case we may be interested in the relationship between the sales of a product and buying power. In the second, we may wish to find the association between major and minor defects of a product. Correlation analysis requires the same procedure in each case.

An examination of what is known as the scatter diagram will give a further insight to the meaning of correlation as a measure of covariance. The scatter diagram indicates the presence of correlation, but will not measure it. In Table 1 are shown data for a certain mechanism on inches drop of a one-fourth pound ball and pounds of force created by the fall. These figures are plotted in Figure 1, each dot representing the relation between distance of drop and force for one trial. It is clear from this scatter diagram that there is a relationship between the two variables, because, in general the greater the fall, the greater the amount of resulting force. Such a relationship is known as positive correlation. In other words, the line through the dots has an upward trend. Had the line had a downward trend, the relation would have been negative. As an example of this, consider the fluctuations in stock prices and their yield. As the prices of stocks increase, their yields decrease. The fluctuations of the two series are in opposite directions, and hence the existing correlation is negative. The positive or negative description of correlation indicates only the direction of relationship -- not the degree of covariance.

Types of Correlation. There are many different types of correlation, the most important of which are discussed briefly below.

Simple or linear correlation. This form of correlation is used when analyzing two variables, if, when the scatter diagram[2] is inspected, it appears that a straight line (or linear equation) would best represent the dots. It should be noted at this point that one variable must be dependent and the other independent, i.e., they must be related in such a way that fluctuations in one logically cause or are related to fluctuations in the other. It is the belief of the writer that non-observance of this rule is one of the major pitfalls in the application of correlation. To clarify this, consider an extreme case -- that of analyzing by the use of correlation the grades of statistics students and the heights of their fathers. This is obviously incorrect because it is immediately recognized that there should be no relationship. However, usually the considered factors are not so plainly unrelated. Conclusions based upon pseudo-correlations may be misleading, and hence worse than no analysis at all. Care must be taken in choosing the factors to be certain that one is dependent and the other independent.

Returning to the data in Table 1, note that the independent variable is the distance drop of the ball and the dependent factor is the resulting force. Another way of expressing it is that differences in the inches drop of the ball cause differences in the forces. Figure 1 indicates that simple correlation analysis is applicable because a straight line best represents the dots.

Curvilinear correlation. If the scatter diagram shows that a curved rather than a straight line would best fit the dots, curvilinear correlation analysis is required. An example of this type is the relationship between rainfall and corn yield. A very small amount of rain

[2]In the construction of a scatter diagram it is customary to plot the independent variable on the horizontal axis and the dependent variable on the vertical axis.

results in a small corn yield. As the rainfall is increased, the corn yield also increases up to the point where the rain is detrimental to the corn, when the corn yield begins to decrease as the rainfall increases. Such data would best be represented by a curve, probably of the second degree.

Multiple correlation. Multiple correlation is applicable when considering the relationship between one dependent variable and two or more independent variables. Suppose we are analyzing the success of many salesmen (as indicated by the amounts of their sales for a company in a given period). We may have reason to believe that factors contributing to their different performances are previous years of selling experience and education. In other words it is thought that experience and education (two independent factors) influence their sales (the dependent factor). An analysis may be made by multiple correlation to find out how much influence the independent factors have on the dependent factor.

Partial correlation. This type of correlation is similar to multiple correlation in that one dependent and two or more independent variables are required. This form of correlation is a measure of the relationship between the dependent variable and one independent variable when, in effect, the other independent variable (or variables) is held constant.

Curvilinear multiple correlation. This, as the name implies, is a combination of multiple and curvilinear correlation. The assumption is made that the relation between the dependent variable and each independent variable is not linear, but curvilinear.

There are many specialized forms of correlation, among which are biserial, fourfold, tetrachoric, and correlation ratio. Because of their specialization, they are less frequently used than those described above.

Correlation Analysis Divided into Three Parts. It is convenient to think of correlation analysis as involving three kinds of measurements:

1. estimating equation,

2. standard error of estimate, and

3. coefficient of correlation.

While these apply to all forms of correlation, we will first consider them in connection with simple correlation.

One of the most frequent uses of correlation is that in which a known relationship between two series is made the basis for estimating one of them from a given value of the other. The estimating equation, often called regression equation, accomplishes this purpose. It is an algebraic expression of the relationship between two variables, the general form of which is $Y = a + bX$, where Y is the dependent variable, and X the independent variable. The equation represents the

straight line which best fits the data and is usually determined by the method of the least squares.[3] This may best be explained by reference to a simple illustrative example, such as that in Table 2.

TABLE 2

X = Time (minutes) required to produce a given product.
Y = Quality rating of product.

Product Number	X	Y	X^2	Y^2	XY	Y_c	$Y - Y_c$	$(Y - Y_c)^2$
1	11	116	121	13,456	1,276	113.74	2.26	5.1076
2	12	132	144	17,424	1,584	125.43	6.57	43.1649
3	9	104	81	10,816	936	90.36	13.64	186.0496
4	20	139	400	19,321	2,780	218.95	- 79.95	6,392.0025
5	12	114	144	12,996	1,368	125.43	- 11.43	130.6449
6	13	180	169	32,400	2,340	137.12	42.88	1,838.6944
7	61	720	3,721	518,400	43,920	698.24	21.76	473.4976
8	16	174	256	30,276	2,784	172.19	1.81	3.2761
9	25	312	625	97,344	7,800	277.40	34.60	1,197.1600
10	31	338	961	114,244	10,478	347.54	- 9.54	91.0116
11	43	465	1,849	216,225	19,995	487.82	- 22.82	520.7524
Total	253	2,794	8,471	1,082,902	95,261	2,794.22		10,881.3616
Average	23	254				254.02		

Regression equation: $Y = a + bX$

$$a = \frac{\Sigma X^2 \Sigma Y - \Sigma X \Sigma XY}{N\Sigma X^2 - (\Sigma X)^2} = \frac{(8471)(2794) - (253)(95,261)}{(11)(8471) - (253)^2} = -14.85$$

$$b = \frac{N\Sigma XY - \Sigma X \Sigma Y}{N\Sigma X^2 - (\Sigma X)^2} = \frac{(11)(95,261) - (253)(2794)}{(11)(8471) - (253)^2} = 11.69.$$

Therefore, $Y = -14.85 + 11.69X$.

Standard error of estimate: $\sigma_{y_s} = \sqrt{\frac{\Sigma(Y - Y_c)^2}{N}} = \sqrt{\frac{10,881.3616}{11}} = 31.45$

$\Sigma x^2 = \Sigma X^2 - \bar{X}\Sigma X = 8471 - (23)(253) = 2652$

$\Sigma y^2 = \Sigma Y^2 - \bar{Y}\Sigma Y = 1,082,902 - (254)(2794) = 373,226$

$\Sigma xy = \Sigma XY - \bar{X}\Sigma Y = 95,261 - (23)(2794) = 30,999$

$$r = \frac{\Sigma xy}{\sqrt{\Sigma x^2 \Sigma y^2}} = \frac{30,999}{\sqrt{(2652)(373,226)}} = .99$$

$$F = \frac{r^2}{1 - r^2}(N - 2) = \frac{.9708}{1 - .9708}(11-2) = 299.22 \qquad \frac{5.12}{10.56.}$$

[3] The method of least squares is based upon the principle that the line which best fits the data is that which renders the sum of the squares of the differences between corresponding actual and calculated values a minimum. The usual methods of the differential calculus are employed for the derivation and lead to a set of equations known as normal equations.

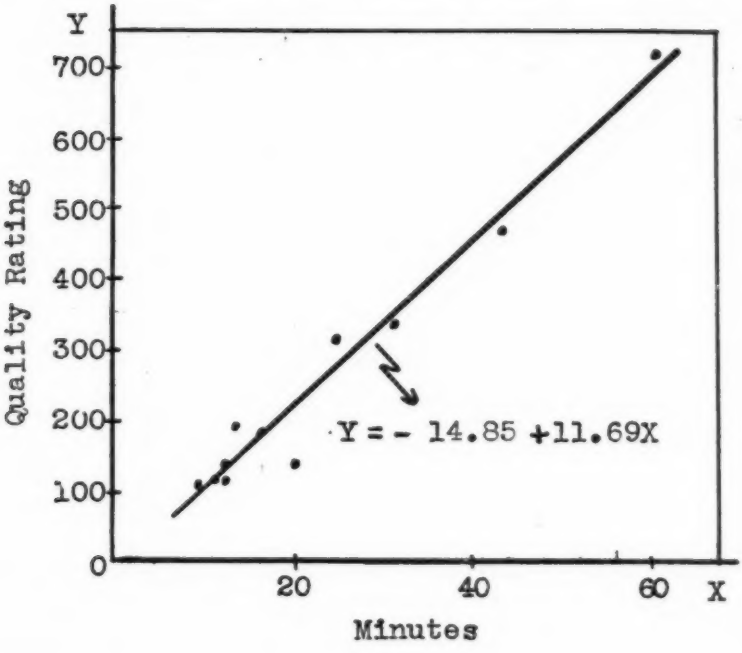

FIGURE 2

The data for this example are plotted in Figure 2, and it will be noted that the relationship between the two series is linear. Since the general form of the straight line of regression is

(1) $Y = a + bX$

it is necessary to find the values of a and b which satisfy the given data. Formulae for a and b are found by solving the normal equations. It should be noted first, however, that the normal equations may be derived upon either of two assumptions:[4]

1. The data of X are accurate, and there is a chance of error in Y, in which case[5]

(2) $$a = \frac{\Sigma X^2 \Sigma Y - \Sigma X \Sigma XY}{N\Sigma X^2 - (\Sigma X)^2} \text{ and } b = \frac{N\Sigma XY - \Sigma X \Sigma Y}{N\Sigma X^2 - (\Sigma X)^2}.$$

[4]There can be a third assumption -- that data of neither X nor Y are accurate. The formulae for a and b are then quite complicated. They are derived on pages 141 and 142, part 1, of reference (8).

[5]In practice these formulae, as well as many which follow in this paper, are simplified. The writer has tried to use those which show the meaning of the different measurements.

(Σ, sigma, is the symbol for the process of summation, meaning "the sum of." N is the number of paired items.)

2. The data of Y are accurate, and there is a chance of error in X, in which case

$$(3) \quad a = \frac{\Sigma Y \Sigma XY - \Sigma X \Sigma Y^2}{N\Sigma XY - \Sigma X \Sigma Y} \quad \text{and} \quad b = \frac{N\Sigma Y^2 - (\Sigma Y)^2}{N\Sigma XY - \Sigma X \Sigma Y}.$$

In fitting a curve to economic, experimental data, etc. the formal mathematical procedure should not be used without first verifying that the underlying assumptions are justified.

Thus, in considering the data in Table 2, we will assume that X is accurate and there is a chance of error in Y, and hence apply the first set of formulae (2). Table 2 shows computations to determine the values which must be substituted.

$$a = \frac{\Sigma X^2 \Sigma Y - \Sigma X \Sigma XY}{N\Sigma X^2 - (\Sigma X)^2} = \frac{(8471)(2794) - (253)(95,261)}{(11)(8471) - (253)^2} = -14.85$$

$$b = \frac{N\Sigma XY - \Sigma X \Sigma Y}{N\Sigma X^2 - (\Sigma X)^2} = \frac{(11)(95,261) - (253)(2794)}{(11)(8471) - (253)^2} = 11.69.$$

Therefore, the estimating equation is

$$Y = -14.85 + 11.69X.$$

This, when plotted, is a straight line representing the trend of the data. The equation enables us to estimate the quality of the product for any given amount of time between 9 and 44 minutes, the limits of the independent variable used in this correlation. A line of regression is valid only between the limits of the factors used in its derivation. To estimate the quality of the product if the production time is 30 minutes, substituting 30 for X in the equation, we have

$$Y = -14.85 + (11.69)(30) = 335.85.$$

The question now arises, "How well does the regression equation represent the data?" If the quality of the product had been affected by only the time required to produce it, the values computed from the estimating equation, Y_c, would have been identical with the actual, Y, and all of the dots would have fallen on the trend line. The differences between corresponding Y's and Y_c's are known as errors of estimate, called <u>standard error of estimate</u>, which is the most useful measure of the dependability of the calculated values of the dependent variable. Its formula may be written

$$(4) \quad \sigma_{y_s} = \sqrt{\frac{\Sigma(Y - Y_c)^2}{N}}.$$

For the example under consideration, the calculated values are shown in Table 2 under Y_c. Substituting in equation (4),

$$\sigma_{y_s} = \sqrt{\frac{10,881.3616}{11}} = 31.4518.$$

In practice, however, instead of calculating the computed values and the errors of estimate, a short cut is used, and the standard error of estimate is generally found by the formula

$$\sigma_{y_s} = \sigma_y \sqrt{1 - r^2}$$

where σ_y is the standard deviation of the dependent variable, the formula for which is

$$\sigma_y = \sqrt{\frac{\Sigma X^2}{N} - \left(\frac{\Sigma X}{N}\right)^2},$$

and r is the coefficient of correlation which will be explained later in this paper.

The standard error of estimate may be interpreted similar to that of the standard deviation of a frequency distribution. It yields an estimate of the range above and below the regression line within which 68.27 per cent of the items may be expected to fall if the distribution is normal. 95.45 per cent would fall between plus and minus two σ_{y_s}, while 99.73 per cent would be between plus and minus three σ_{y_s}. These, of course will not hold true if the sample is small or the scatter is not normally distributed around the estimating equation.

Another measure closely related to the regression line and the scatter around it is known as the coefficient of correlation, r, in linear correlation. The standard error of estimate gives a gauge of the amount of variation in the dependent variable which we have failed to account for by the regression equation, but it is stated in terms of the original data of the dependent variable -- in the case of our example, quality rating of the product. When considering the relation between two variables, it is convenient to express the results in numerical terms which are independent of the units of the original data. The coefficient of correlation serves this purpose. Another advantage of this measure is that one coefficient can be compared with any other regardless of the terms of the data of the different correlations.

The coefficient of correlation is a number varying from + 1, through zero, to - 1. As has been explained the sign indicates the slope of the regression line. It is the magnitude of the coefficient which measures the degree of relationship. When there is absolutely no covariation between the variables, r is zero.

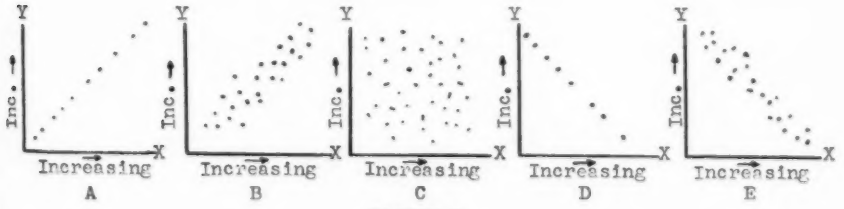

FIGURE 3

In Figure 3, Diagram A is an illustration of perfect positive correlation, r = + 1. In Diagram B the points do not lie along a straight

line, but there is a definite tendency for the values of the Y data to increase with the values of the X data. Therefore we can say that the scatter shows positive correlation. In Diagram C there is no tendency for the points to follow any relationship, and hence there is zero correlation. The points in D follow a straight line, but the values of the dependent variable decrease as the independent variable increases. This is known as perfect negative correlation, $r = -1$. The points in E like those of B do not follow a straight line, but do show a tendency to cluster about a line. Therefore we can call this negative correlation, because the values of one variable tend to decrease as the values of the other variable increase.

A clear understanding of the meaning of the coefficient of correlation may be gained by the following approach. One measure of variability of the Y values is the square of the standard deviation of the Y values, called variance, or total variance. The total variance may be broken up into two parts -- that explained by the regression line and that which has not been explained. The amount of variability which has been explained by the estimating equation may likewise be measured by the square of another standard deviation, namely that of the Y_c values from their own mean (which is also the mean of the original Y values). The unexplained variance is the square of the standard error of estimate. Thus for our example in Table 2 we have:

Variance	Formula	Amount of Variance	% of Total Variance
Unexplained	$\sigma_{y_s}^2 = \frac{\Sigma(Y - Y_c)^2}{N}$	989.2147	2.92
Explained	$\sigma_{y_c}^2 = \frac{\Sigma(Y_c - \bar{Y})^2}{N}$	32,940.4217	97.08
Total	$\sigma_y^2 = \frac{\Sigma(Y - \bar{Y})^2}{N}$	33,929.6364	100.00

($\bar{Y}$ is the arithmetic mean of the Y values.)

The coefficient of determination, r^2, is the proportion of total variance which has been explained, .9708 in the above case. The coefficient of correlation, r, is the square root of the coefficient of determination. Therefore, the coefficient of correlation (.99) may be thought of as the square root of the proportion of variance which has been explained by the independent variable.

The usual method employed to find r is not nearly as laborious as the one shown above. One of the most frequently applied formulae is

$$r = \frac{\Sigma(X - \bar{X})(Y - \bar{Y})}{\sqrt{\Sigma(X - \bar{X})^2 \Sigma(Y - \bar{Y})^2}} \tag{5}$$

where $\bar{X} = \frac{\Sigma X}{N}$ and $\bar{Y} = \frac{\Sigma Y}{N}$. Equation (5) can be simplified to

$$r = \frac{\Sigma xy}{\sqrt{\Sigma x^2 \Sigma y^2}} \tag{6}$$

where $\Sigma x^2 = \Sigma X^2 - \bar{X}\Sigma X$, $\Sigma y^2 = \Sigma Y^2 - \bar{Y}\Sigma Y$ and $\Sigma xy = \Sigma XY - \bar{X}\Sigma Y$. (6) is the principle formula for r, and is called the Pearson product-moment formula. The calculations are simple, and do not require finding the equation of the regression line.

Substituting in equation (6) for our example in Table 2, we have

$$r = \frac{\Sigma xy}{\sqrt{\Sigma x^2 \Sigma y^2}} = \frac{30,999}{\sqrt{(2652)(373,226)}} = .99.$$

In the development of the Pearson product-moment formula for r, no assumptions are made regarding the shape of the distributions in the correlated series. The formula is general; it holds for distributions of any shape.

The next question to be considered is, "How reliable is the coefficient of correlation?" Obviously, a major factor determining that reliability is the size of the sample, since the smaller the items the greater the possibility of accidental covariation. The question of confidence in the correlation coefficient at one time was answered in terms of probable error. However, statisticians have long ago stopped talking about probable errors. There is nothing particularly wrong with them; they are simply outmoded, like the Model T Ford. A more dependable method has been devised by the English statistician, R. A. Fisher. A full explanation of the basis of the test for significance is not appropriate for this paper. However, it is possible to describe the simplest and most satisfactory way.

Tables and charts are available showing for different sample sizes drawn from normally distributed universes, the highest coefficient of correlation that might appear by chance once in 20 times (called the 5 per cent level) and once in 100 times (1 per cent level). If the coefficient found is greater than that which might appear by chance once in 20 times, but less than that which might appear once in 100 times, it is said to be <u>significant</u>. If the coefficient is greater than the 1 per cent level, it is said to be <u>highly significant</u>. The conclusion to be drawn in the first case, and particularly in the second case, is that the magnitude of the correlation coefficient is not due to chance.

A more general method of evaluation applicable to r is supplied by what is known as the F table,[6] so named because of Fisher's work on the subject. It gives the 1 and 5 per cent levels of F for designated degrees of freedom in the greater and smaller mean square. To use the table, the following calculation must be made:

$$F = \frac{r^2}{1 - r^2} (N - 2)$$

$$F = \frac{.9708}{1 - .9708} (11-2) = 299.22.$$

[6]See reference (2), pp. 568-569.

Reading from the F table we find that the 5 per cent level is 5.12 and the 1 per cent level is 10.56. The obtained value of F is far greater than the 1 per cent level and we may conclude that the correlation coefficient is highly significant.

The important steps in linear correlation have been described above. The procedures of multiple, curvilinear, partial, and combinations of these three types are similar but more complicated. In analyzing by correlation m variables, it is necessary to solve m - 1 simultaneous equations for m - 1 unknowns (called b's in the estimating equation). A great aid in the solution of the equations is the Doolittle Solution.[7] This method is not difficult, and when once learned, may be applied when needed in any correlation.

Limitations of Correlation Analysis. It is important that we understand the limitations of correlation and not merely work with its formulae as magic. The interpretation of the results "abounds in pitfalls easily overlooked by the unwary while they are cantering gaily along upon their arithmetic." The required calculations have been greatly systematized. However, the set-up of the analysis and the explanation of the results, after they are found, require consideration and thought.

No measure of correlation, however great, proves the existence of a relationship between the compared variables. It merely indicates that such a relationship may prevail. Their similarity may be the result of other changing series affecting each variable in the same way, or in opposite ways. The classical example is that there was a high degree of positive correlation over a period of years between teachers' income and the amount of money spent for liquor. The conclusion to be drawn was not that the increase in liquor sales was caused by the increase in the income of teachers. The underlying variable was national income, fluctuations in which caused variation in both liquor sales and teachers' income. Also this correlation could be ruled out on the basis that there was no independent variable in the analysis -- only two dependent factors (both dependent upon national income).

A high correlation coefficient may be due to pure chance. Thus it might be found that in a certain group of workers there is positive correlation between their ages and the number of pennies in their pockets at a certain time. Even if the coefficient were quite high, it would be difficult to develop a theory as to why there should be such a relationship. Chances are that another sample would yield quite different results. Therefore, the interpretation of any measure of correlation must be supplied not from the statistical analysis alone, but from an understanding of the common causes or other relationships between the series correlated.

As mentioned previously, the correlation coefficient and the regression equation should be regarded as valid only within the range of data used. The association may not hold true outside those limits.

[7] See reference (10), pp. 226 - 238.

Applications of Correlation Analysis. For a great many years correlation analysis has been applied to problems in economics, sociology, marketing, business administration, agriculture, and biology. The physicist, astronomer, and research worker have found such analysis to be a useful tool. More recently, however, correlation has been widely used in industry. The difference may be attributed to the lack of statistics courses in most engineering curricula. It is the opinion of many that, with the advancement of statistical quality control, there will be a demand for engineers to be acquainted with the fundamental concepts of statistics, including correlation, and such courses will be offered in engineering schools.

In the space allotted for this paper it is not possible to cover all aspects of correlation analysis. The subject requires some serious study. For those who wish to pursue it further, the following references are suggested:

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PRACTICAL APPLICATION OF QUALITY CONTROL TO THE PROBLEMS OF GARMENT MANUFACTURING

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The application of the principles of quality control by statistical methods to the manufacturing of garments might at first appear to be quite a problem. It might appear to be a problem because of the nature of the industry, an industry wherein most of the operations deal with the human element; that is, operations not mechanically performed in whole. At first one might be inclined to believe that such operations do not lend themselves to statistical control; but this is not true.

When we think of quality control by statistical methods and read of the results obtained by its many uses in the machinery field, we can readily understand that with parts produced by machines, many operations of which are automatic, with machines that can be set to continue to produce repetitive operations with a fine degree of accuracy, these operations can easily be controlled statistically and a very close control placed on the work or output in such cases. To set up such workable controls and tolerances does not present a difficult problem, particularly when the operations are largely mechanically performed.

Now with respect to garment manufacturing, where the individual enters so much into the picture and the materials used and worked with are cotton, wool, silk, rayon, et cetera, - materials that do not lend themselves readily to automatic handling, questions doubtless come to mind. Will quality control by statistical methods work? Is it practical? To these questions, the answer is "Yes". The opportunities for quality control in the garment industry are as great and as productive of worthwhile results as in any other industry.

The practical application of these principles in the garment industry or textile field may differ somewhat from the practical application of the same principles in the heavy industries, but the results will be the same--improved quality and better merchandise. Nevertheless, the following questions are likely to be raised: Where should these controls be set up? How should they be worked? What records are to be kept? What use can we make of these records? Should we use charts? Where, when, and how? Not only "where, when and how", but also "why".

Quality control in the garment industry, as in many other industries, must start in the receiving department. Many people do not like that word "must", but in quality control it belongs. The receiving room, or department, must be set up to inspect a percentage of all incoming raw or manufactured materials that are used in the makeup of finished products. You owe this protection to yourself as a manufacturer. By inspecting a percentage or a cross section of incoming materials, you assure yourself of a good start in the production of quality merchandise. By following this procedure you assure yourself that the materials you are going to work with are of the proper

quality, and you do it today--not weeks later when the discovery of poor raw materials or parts could cause a serious interruption of your work program. What percentage of incoming materials should be inspected can best be decided by a study of your operations and your particular needs. A five per cent inspection may be the answer for one manufacturer, ten per cent for another, and for another perhaps fifteen per cent. It is up to you to work out the particular percentage needed through careful study.

You may wish to go as deeply into your inspection of incoming materials as we do at RELIANCE, and that is to give these materials laboratory testing. We have our own laboratory in our RELIANCE building. It is an expensive layout, but we consider the results obtained, and to be obtained, well worth the cost. There is also another angle to incoming inspections, and an important one. It provides information as to just who is who in the supplying of quality materials. By calling the attention of suppliers to any substandard material shipped, you put them in a position to get their house in order. Everyone benefits from this procedure.

What to look for in your inspection is for you to decide. What is acceptable in cotton goods may not be acceptable in silk. What one manufacturer may receive as acceptable, another may reject. You are the guardian of your quality standards. You know what you are shooting for. It is not a bad idea to get together with your suppliers and have an understanding as to what will constitute acceptable quality. Then set your standards accordingly, and stick to them.

In referring to the inspection of incoming materials, I said it was a protection we owed ourselves. None of us are in an industry where we can afford to be selfish and think only of ourselves. We must think of our customers. They are the people who keep us in business, and we owe them protection--the protection of supplying them with quality merchandise. The supplying of quality merchandise can only be assured by the closest attention to each and every detail of manufacturing, and to the setting up of controls that will insure quality merchandise.

Where, when, and how should these controls be set up? We, in the garment industry, realize that the producing of quality merchandise starts in the cutting room and continues through the sewing operations to and including finishing. It is true we can do a lot in the finishing room or pressing department, but we all know that real quality, that something that makes for serviceability, is built into the garment --not pressed into it. Therefore, we must start with our cutting or foundation and set our first controls there. What these controls should be must be determined in the light of your problems from the point of obtaining the piece goods to the delivery of the cut goods into the stitching room. A proper control in this department is not difficult to set up, and I doubt if there are any of you who do not have some inspection in your cutting department. But is it thorough, and is it done intelligently and systematically, and do you know what is happening? Are you keeping records and charts? If not, you should. You will then know just where you are going and how.

In the stitching room the setting up of quality control stations will depend a great deal upon the garment made. These quality control stations do not and will not eliminate supervision. They will assist supervision. The continual round of inspection by foremen and floor-ladies at the machines is essential. It is a "must", and I know of nothing that can take its place. The quality control stations will be of immense value in helping to assure quality merchandise through the inspection of a percentage of all parts or assemblies passing through such stations. They lead to the prompt correction of errors, whether caused by the operator or by machine failure, to the keeping of accurate records and charts that reveal current quality experience, and also to records that make it possible to discover who is doing a good job and who is contributing to the poor work. Records such as these are invaluable. These are records that management can use to great advantage. They show what happened yesterday, and what is happening today. They are the lighthouses that will guide you into the harbor of quality merchandise. The number and location of these control stations will depend upon the garment being manufactured. The percentage of each lot or bundle looked at will best be determined by your experience and a careful study of your particular garment and set-up.

Continuing on to the finishing department, we must also have here controls, charts, and records. This is the department charged with the responsibility of taking the product of the cutting room and stitching department and working into it that finish, that something known as "eye appeal", that million dollar look, which combined with serviceability that is quality made merchandise will keep the customers asking for more and more and coming back year after year because they are satisfied. We all know that only quality merchandise satisfies.

The keeping of a control chart for sewing operations and the setting up of tolerances, that is upper and lower quality control limits, in the garment industry may appear to present somewhat of a difficult problem because so much of the work consists of the matching and sewing together of parts, many of which are not the same size or shape. We will defer consideration of the sewing operations and the complete solution of this problem for a while.

Quality control charts can be kept very easily with respect to measurements or specifications. The zero or center line on such a chart would be the specification or measurement for the part or parts of the garments. The upper and lower limits would be the permissible variation from specifications, limits which naturally would vary throughout the garment. For example, where one-half inch plus or minus in the length of the leg of a work pants may be acceptable, the same tolerance in the front rise may not be acceptable. Charts for this purpose would have to take into consideration the many parts of a garment that make up the specifications. Therefore a chart, or charts, would be in order to cover each of the different specifications or allowances. Some of these specifications or allowances may be combined with others of like kind or allowance. Charts such as these can be easily kept, and with very worthwhile results, thereby building up records and statistics that will prove very valuable.

What the tolerances should be is a decision that must be left to each and every manufacturer. He knows best his product and what will be acceptable to his trade.

Coming back to the sewing operations, valuable and easily kept charts can and should be prepared for these operations. The best chart for this purpose is probably the percentage and bar chart. This can be a combination chart plotting the percentage on the upper half and the individual operations on the bar or lower half. The individual operations and the percentage chart figures are plotted from the records kept by the inspectors at the quality control stations. These charts will show graphically what operations are out of line, and point to the spots where prompt action is necessary. The charts should be large enough to command attention, and should be posted in the workroom where they can be observed by all of the workers. Supervision should highlight these charts and help build up the interest of employees in them.

Quality control by statistical methods is not something to do away with time tested methods. In the making of quality merchandise there will always be a place for spoken words or lectures on the subject. There will always be a place for the manuals, bulletins, and letters that deal with quality. Quality is something that does not grow better. A tree will grow, but quality is made better, made better by the intelligent use of the data brought to light through the quality control program, and by the daily follow-up. By "follow-up" I mean getting in there and correcting now the things shown by quality control to be out of line. It takes constant follow-up on the part of every one, because quality control is the job of every one--the job of producing the kind of merchandise that our customers can be proud to sell, the consumers proud to wear, and we proud to put our name on. Therefore, let us use this new tool of quality control by statistical methods to help do a better job in a scientific way and at a lower cost.

SAMPLING AND SORTING AMMUNITION FOR THE ATTACK ON NORMANDY

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Introduction. The quality control techniques which I shall discuss are relatively simple and well-known. My objective is not so much one of presenting the statistical techniques as that of emphasizing the importance of knowing thoroughly the scientific, engineering, or other technical aspects of the field to which one's statistical attack is to be applied and of calling attention to the value of various intangible factors which affect any technical enterprise. A lack of appreciation of the technical aspects of a problem may result in a statistical analysis which is inapplicable or wholly wrong. Lack of professional reputation, prestige, or influence may be a cause of lack of opportunity to do fruitful quality control work or may result in useless quality control work because of inability to get menagement to take appropriate action in accordance with the results of a quality control analysis.

Statement of the Problem. A few months before the Allied attack on France the Army became very disturbed about a technical artillery problem which affected the tactical situation. Artillery ammunition is normally made in lots. Within the lot the ammunition is supposed to be reasonably uniform in the sense of a population or statistical universe. However, ammunition is presumed to vary considerably from lot to lot. For example, when the artilleryman is firing rounds from a single lot of ammunition he expects to encounter only the variation associated with the standard deviation or probable error of the ammunition lot. However, it is recognized that the mean values or centers of impact of lots of ammunition differ. Therefore, it is normal practice for the artilleryman to conduct trial fire upon each change of ammunition lot, in order to determine experimentally the initial correction associated with the lot of ammunition at hand. In the amphibious attack upon Normandy, it was contemplated that it would neither be practicable to supply units with single ammunition lots of sufficient size for the mission nor to afford the artilleryman opportunity to conduct trial fire on change of ammunition lots. Therefore, it was desired that a large quantity of ammunition be supplied which was so uniform that it would make little or no difference if the artilleryman changed from lot to lot during the conduct of fire.

These precautions were essential in order to reduce the chance of inaccurate barrages which could result in rounds falling among our own troops. The Ballistic Research Laboratories were asked if they could correct quickly a situation which had been traditionally tolerated as a necessary evil. There was no time for the manufacture of special ammunition. There was scarcely enough time for sampling and sorting a large quantity of the ammunition already delivered to England. It was necessary to achieve swiftly and under congested conditions a result which neither the Ordnance Department nor industry had here-to-fore been able to achieve either in peace-time manufacture or in the relatively undisturbed conditions of the Zone of Interior.

Why Q.C. Got the Job. Why did the Army or more specifically the Ordnance Department turn to quality control for the solution of so impor-

tant and urgent a problem? Certainly it was not because top management knew anything about mathematical statistics, or even very much about industrial quality control. Unquestionably the Laboratories got the job because of reputation. During the preceding years the Laboratories had repeatedly used quality control techniques to save the Ordnance Department time and money, while at the same time greatly improving the product. The Laboratories had been very careful about their quality control work because hardly anything can hurt the advancement of a new idea as much as a failure which is subject to the merciless criticism of reactionary men.

Conditions for Accepting the Problem. The Laboratories did not accept the problem without some conditions. They stated that success could be promised only if three conditions were met; namely (1) that a team of at least four persons be sent together with approximately two tons of equipment; (2) that the cooperation of the Theater of Operations be promised to the extent of giving the services of one to four battalions of troops; (3) that action be taken by the theater in accordance with the recommendations of the team. These conditions were met.

Preliminary Considerations. Although I was head of the team I did not even bother initially to think about the statistical techniques which I was going to employ. I was sure I could think them up on the long airplane flight across the Atlantic, and quickly complete the design of experiment with some expert assistants, after surveying the local conditions. First, I looked to selecting my team. I got a first-rate quality control engineer, Mr. Frank E. Grubbs, because I was sure I would be concerned with explaining things to the high command, to the artillery, and to the British; that I would be left with little time for technical quality control work. Second, I selected a good ordnance engineer, Mr. Louis Zernow, because I knew there would be a huge ammunition sampling problem which would have to be administered efficiently and properly. Third, I selected a good electronics engineer, Mr. Norman Arnold, because the testing of samples would consist of determining the velocity and range of a large number of projectiles fired from guns and this is a difficult problem in ballistic measurements. Mr. Arnold's electronic equipment took most of the two tons of baggage allowance.

Mr. Grubbs and Mr. Zernow anticipated both the lack of data and confused conditions likely to be encountered in the Zone of Communications. They scurried about and obtained copies of ammunition data cards and similar records so that progress of work would not be hampered by lack of basic technical information such as the number of projectile lots in an ammunition lot, the powder lots that went into various ammunition lots, and similar information. They saw to it that the team went fully equipped even with information that it had a right to expect at the place of work. It is almost axiomatic that to do his work well, the quality control engineer must know more or have available more information on the technical aspects of his problem than even the specialized personnel who work constantly in that field.

The Quality Control Technique. If repeated shots are fired from a gun at a certain elevation there are really only two reasons why all the shots do not hit at the same place. These are: (1) the shots do not

leave the muzzle of the gun with exactly the same velocity and (2) the shots all do not behave the same after they have left the muzzle of the gun. Technically, the former is interior ballistic variation and the latter is exterior ballistic variation. There are three major causes of these two types of variation: (1) the amount of powder in the charge, (2) the character of the rotating or driving band, and (3) the surface finish of the projectile. These three causes affect both the within-lot dispersion and the lot-to-lot dispersion. The whole concept can be expressed briefly and approximately as shown in Table I.

TABLE I

Cause	Ballistic Effect	Increased Variation	
		Within-lot	Lot-to-lot
Establishment of charge	Interior	No	Yes
Banding	Interior	Yes	Yes
Surface Finish	Exterior	No	Yes

In a single lot of ammunition, each of these three causes, powder charge, banding, and surface finish, affect both the average range of the projectiles and the dispersion in range of the projectiles. A single ammunition lot contains only one powder lot, but the same powder lot may go into several ammunition lots. A single ammunition lot may contain a number of projectile lots, but the same projectile lot may appear in a number of ammunition lots. If one can measure the extent to which the three causes tabulated in the first column of Table I influence the effects listed in the second column, one can infer quantitatively the principle quality characteristics of all lots of ammunition composed of the known components and be able to grade them and classify them according to quality. For these, and hence, the other reasons, an economical solution of the problem is not that of sampling ammunition lots, as the artilleryman or ordinary engineer would suspect, but the sampling of the component powder lots and projectile lots.

If we designate the effect on nominal or expected range as $\Delta\bar{x}$ and the effect on dispersion as R, then for the three causes we can designate the effects on quality by the following six symbols:

$\Delta\bar{x}_p$, change in range due to powder

R_p, variation in range due to powder

$\Delta\bar{x}_b$, change in range due to banding

R_b, variation in range due to banding

$\Delta\bar{x}_e$, change in range due to surface finish

R_e, variation in range due to surface finish.

By sampling the component lots (powder lots and projectile lots) these parameters can be evaluated. Then, for any ammunition lot, the deviation of range from nominal will be the algebraic sum of the $\Delta\bar{X}$'s and the dispersion of the lot (standard deviation or probable error) will be the square root of the sum of two quantities, one of which is the sum of squares of the average effects $\bar{R}_p$, $\bar{R}_b$, $\bar{R}_e$ and the other the variance among shell lot averages.

The Viewpoint of Quality Control. Let us briefly examine the sorting problem from the viewpoint of quality control. The ammunition lots are composed of powder lots from various manufacturers and of projectile lots from various manufacturers. Hence, there is no reasonable expectation that the flow of ammunition lots (even from a single assembler of ammunition lots) will exhibit statistical control. Hence, ammunition lots can be sampled only on the overwhelmingly extravagant basis of determining the quality of unique lots.

However, ammunition experience shows that groups of component lots from a single manufacturer have a good probability of exhibiting statistical control, even though the manufacturers may not use statistical methods. Thus, by sampling the component lots powerful quality control techniques become applicable. Furthermore, the information economically gathered by quality control techniques can be validly applied to the assembled ammunition lots even though they do not exhibit control.

The problem may be regarded as applying the principles of quality control after manufacture for the purpose of quality determination. However, the action taken when there is a lack of control is different. The usual action of the production process is not possible and is inapplicable to the problem of sorting. If there is lack of control with respect to dispersion, the uncontrolled product must be discarded; i.e., for this case it is impracticable to apply ballistic corrections. If there is a change in average value, this is merely noted for grading purposes with a view to applying an appropriate ballistic correction to the sorted product. Of course, the accumulation of $\Delta\bar{X}$'s or of R's may result in the discard of complete ammunition lots made from controlled component lots.

Technique of Application. The principle objective of the procedure was the sorting of approximately a million rounds of 105mm ammunition (the type used most by the Field Artillery). Since the ammunition on hand consisted of somewhat more than a million rounds which had been manufactured in almost continuous production by various manufacturers, quality control charts could be constructed much the same as they would have been constructed during manufacture if the lot of each respective component was the rational subgroup for sampling purposes. These are matters of routine in industrial quality control.

Much could be said about the various special measures that had to be taken to conform to various technical considerations concerned with ballistics of ammunition; and also much could be said about the methods used whereby what was essentially a statistical task was accomplished using only untrained men of ordinary abilities. The former are the features on which one fails if he does not know thoroughly the technology of the field of endeavor to which his quality control work is

being applied. The latter are features of administration and management. A detailed account of these operations would not be of general value. Fortunately all of the team, except the electronics expert, knew the technology of ammunition design, development, and manufacture. The ammunition expert did an excellent job of giving simple instructions to the hundreds of men required to sample the dumps of ammunition which were scattered along over two hundred miles of English roads. The statistician did an excellent job of breaking the analytical process down into small simple tasks and giving each selected enlisted man a simple task to do which was described clearly and briefly. In like manner, the electronics man quickly assembled a team for taking the velocity measurements and drilled each member of the team in a simple task so that he could learn to do it well in only a day or two. Within five days after arrival in England we were shooting, taking measurements, and analyzing data. In six weeks the whole job was over. The results are shown graphically in Figure 1.

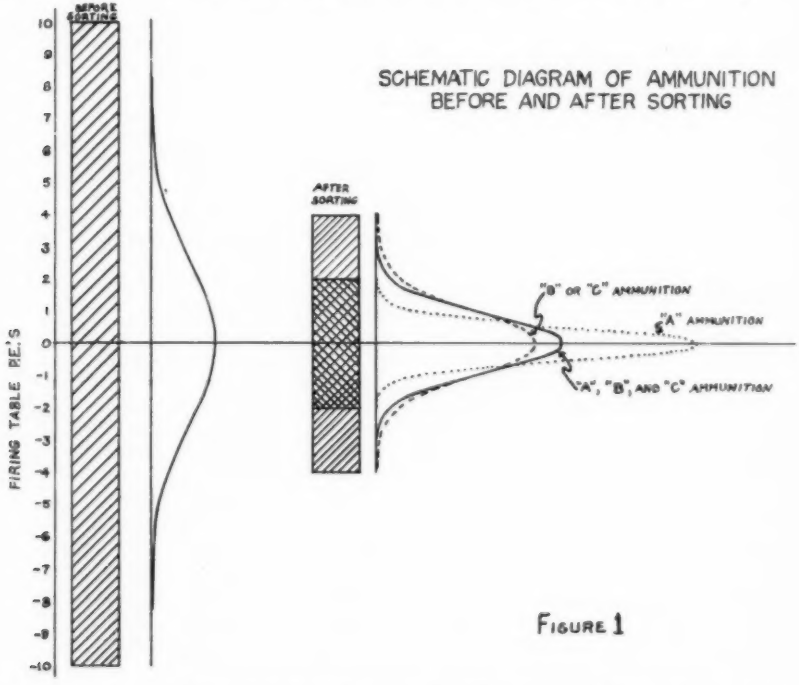

FIGURE 1

Results of Sampling and Sorting. A sample of one-third of one percent was required to determine quality with precision consistent with the sorting plan. The useable ammunition lots were grouped into three super lots designated as white, blue, and red. White was ammunition of very superior quality in which the centers of impact of its various ammunition lots fell within ± two firing table probable errors of the nominal range. Blue consisted of ammunition which normally would have shot beyond the target with centers of impact falling between two and ten probable errors beyond the target. An initial correction was given for the artilleryman to use when firing blue ammunition which

brought the center of the distribution down to the nominal range, thereby making blue ammunition a super lot in which centers of impact of its lots would fall between plus four probable errors and minus four probable errors of the target. Red ammunition consisted of ammunition which would have shot short of the target by two to ten probable errors. A correction was given for this super lot of ammunition so as to bring the center of the distribution to the target line thereby making it consist of lots of ammunition which would shoot within plus or minus four probable errors of the target. Twelve percent of the ammunition graded had to be classified as unserviceable either because of changes in average level of quality beyond tolerable limits or because of excessive dispersion within the ammunition lot.

Each box or crate of ammunition was painted with a red, white, or blue band so that there would be no mistake with regard to its grade. This alone was a huge task for the Ordnance troops in England. The ammunition was then palleted; i.e. placed in stacks of convenient size for easy handling. Clear-cut orders were issued to all troops designating how much of each kind of ammunition every combat unit would get, and the corrections to be applied when using red band or blue band ammunition.

Promotion Considerations. I would like to emphasize again that the quality control details were not the more important ones. The statistical techniques used are well known, and require only thoughtful and valid use in the design of the experiment. It is more important to observe that the opportunity to use the technique was gained by virtue of a reputation for success based more on careful attention to the technological aspects of fields of science and industry than on superiority in the use of quality control techniques.

However, getting the job and knowing how to do the job is not enough. The authority and prestige of the whole Ordnance Department would not be sufficient to force a new idea of thi sort on the troops unless the artillerymen themselves w e convinced of its merit and practicality. Furthermore, selling a new but superior idea generally consists of first pointing out clearly the advantages of the new idea over one or more old but inefficient ideas. In this instance the artillery had already started its own classification which consisted of sampling each ammunition lot in an attempt to determine its quality and to determine an appropriate correctioh for each and every one of hundreds of ammunition lots. It was necessary to gain an audience with leading artillerymen and show them (without offending them) the infeasibility of determining the quality of a lot by small samples from the lot. This sampling of unique lots would have required such large samples that little or no ammunition would have been left for the attack on Normandy, even if the experiment could be completed in time.

Among the variety of ideas was one for separating the whole mass of ammunition into approximately ten super lots based on grade relative to their shooting over or short of the target. It was necessary to show that known sampling technology does not yield sufficient precision of the mean values for successfully sorting into more than three or four categories, when the number of components is very large and the sample size is of necessity small.

Finally, it was necessary to sell a novel plan--to show that it is better to sample the small constituent elements of the aggregate (whole mass of ammunition) than it is to sample the categories of assembled elements (lots themselves). The artilleryman had to be shown that more information about the lot can be gained from sampling the constituent elements of all the lots than from sampling the lots themselves. This condition is a consequence of the rather well-known principle that sampling should be done one echelon lower than the category about which one wishes to make his statistical prediction.

Everybody loves the spectacular and consequently much support for the quality control idea was gained from the amusing point that by using the proposed technique, one was able to assess accurately the quality of some lots of ammunition which he did not sample at all. This selling job consisted of appearing before groups of artillery officers and also groups of British officers and explaining the entire problem to them in language relatively free from ballistic and statistical terminology. One must understand the problem of the men whose work will be affected by one's quality control techniques; not appear to be ignorant of their problems or unsympathetic in attitude, even though they may inject irrelevant issues and voice objections based on invalid grounds. One must not only explain the elementary mechanism of quality control, but must show the customer that he understands and appreciates the ultimate problems sufficiently to do the quality control work from the sole viewpoint of helping him and not by any chance with the slightest view to mere exploitation and advancement of a quality control technique. This sort of thing is tedious, especially if one is in a hurry, but if the selling job is neglected the whole project fails.

I sometimes wonder how much the use of industrial quality control could be advanced if we took time to make a point of consciously cultivating within ourselves a maximum of genuine interest in the welfare of the consumers of our quality control. The consumers should feel assured that the quality control man's primary interest is the forwarding of their work, while the statistical techniques are regarded merely convenient tools or accessories for the most swift and economical advancement of the consumers' interests.

A Valuable By-Product. When I arrived in Normandy a few days after D-Day, I was most gratified to find that it appeared that no round of our ammunition had fallen among our own troops. I regarded this as the end point and as the mark of success of the sampling and sorting problem. It was not until months later, when I was talking with the Chief of Ordnance Technical Intelligence, that I discovered that I had neither recognized nor anticipated an important by-product of the sampling and sorting job. He stated that, whereas the sampling and sorting procedure had solved the problem that was presented for solution, in his opinion the more important things were confidence of the troops in their weapons and the consequent stimulus given to the morale of the troops. He stated that the general understanding of the solution of the ammunition dispersion problem and wide-spread confidence in its successful solution did much to change worried troops into confident and aggressive troops, and that this gain was probably more important than the material gain in artillery accuracy. This important by-product should not be attributed to technical quality control but to some of the attendant things one should do to make quality control successful.

CLINIC PAPERS NOT AVAILABLE

Clinic No.

3. **"Quality Control in Spring Manufacture".**

   F. C. Schulze, Chief Inspector, Hunter Pressed Steel Company, Lansdale, Pennsylvania.

9. **"Quality Control Versus Piston Rings".**

   R. H. Colvin, Product Engineer, Burd Piston Ring Company, Rockford, Illinois.

13. **"Quality Control in Penicillin and Pharmaceutical Industries".**

    Roland H. Noel, Director of Control, Bristol Laboratories, Syracuse, New York.

16. **"Quality Control Proves Itself in Assembly".**

    Dr. Martin A. Brumbaugh, Bristol Laboratories, Syracuse, N. Y.

21. **"Quality Control in the Paper Industry".**

    J. B. Catlin, Assistant Technical Director, Kimberly-Clark Corporation, Neenah, Wisconsin.

23. **"Use of Shewhart Techniques in Testing Controlled Product".**

    Miss Bonnie B. Small, Engineer, Quality Control, Western Electric Company, Inc., Chicago, Illinois.

27. **"Some Applications of Quality Control to Hybrid Corn Production".**

    Simon Casady and Delmar E. Henderson, Pioneer Hi-Bred Corn Company, Des Moines, Iowa.

33. **"Application of Sampling Plans to the Incoming Inspection Function".**

    A. J. Winterhalter, Colonial Radio, Buffalo, New York.

35. **"Sampling Plans for Continuous Production".**

    H. F. Dodge, Quality Results engineer, Bell Telephone Laboratories, New York City, New York.

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